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ABSTRACT

Many aspects of string theory are abstract and difficult for even theoretical physicist to fully comprehend. The activities in this guide are designed to help teachers and students better understand some of the basic concepts underlying particle physics and string theory. A list of additional resources and a glossary are also included. Each activity includes a teacher activity setup page with background information, an activity objective, a materials list, a procedure, and concluding remarks. Reproducible student pages are also included. (Author/SOE)

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Fall 2003 Teacher's Guide

NOVA

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11 Dimensions?
Parallel Universes?
Is String Theory for Real?
Find out on *The Elegant Universe*
Oct. 28 and Nov. 4, 2003
www.pbs.org/nova

SE-0817

A child's reaching his or her potential is rarely achieved alone. But with great teachers and the right tools (and hard work, of course), children can realize their dreams.

Thanks to the dedication and passion of teachers, confidence in those dreams flourishes. A great teacher recognizes a child's potential, develops it, and points it in the right direction. We salute those who give children the skills they need to keep reaching higher, to never stop learning.

We support the work of NOVA because it, too, helps children reach their potential. After more than 30 years, NOVA continues to explore, inform, and inspire curious young minds. By giving children a tool of such depth, NOVA helps train tomorrow's scientists, explorers, and inventors.

And the teachers who help others reach their full potential may thereby get a little closer to reaching their own. They inspire us, and they inspire all we do.

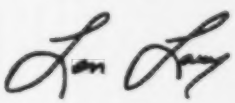
Microsoft

As a teacher, there is clearly nothing more important than connecting directly with your students. That's why Sprint is proud to support the newest generation of programs in the informative, award-winning NOVA series.

Now in its 30th year, NOVA offers a unique virtual window into the high-tech world in which we live and work. The series remains at the forefront of science, educating and inspiring with an in-depth look at the latest discoveries and innovations.

Since 1997, Sprint has connected thousands of teachers, parents, and students across the country through a variety of community relations programs. We are pleased to continue opening the lines of communication and exploration in the classroom and beyond through our sponsorship of the *NOVA Teacher's Guide*.

Sincerely,



Len Lauer
President
PCS Division, Sprint

Sprint.

Contents & Broadcast Schedule

NOVA Teacher's Guide FALL 2003

page		Earth & Space Science	General Science	Life Science	Physical Science	Social Studies	NOVA Activity
2	**NOVA in the Classroom**						
4	**Infinite Secrets*** Tuesday, Sept. 30 • www.pbs.org/nova/archimedes/				●	●	
	Who Killed the Red Baron?* Tuesday, Oct. 7 • www.pbs.org/nova/redbaron/		●			●	
	Lost Roman Treasure (R)** Tuesday, Oct. 14 • www.pbs.org/nova/zeugma/		●			●	
	The Perfect Pearl* (R) Tuesday, Oct. 21 • www.pbs.org/nova/pearl/			●		●	
8	**The Elegant Universe* (3 hours)** **Einstein's Dream**—Hour 1 **String's the Thing**—Hour 2 Tuesday, Oct. 28 • www.pbs.org/nova/elegant/ **Welcome to the 11th Dimension**—Hour 3 Tuesday, Nov. 4 • www.pbs.org/nova/elegant/				●		
	Wright Brothers' Flying Machine* Tuesday, Nov. 11 • www.pbs.org/nova/wright/				●	●	
	Magnetic Storm* Tuesday, Nov. 18 • www.pbs.org/nova/magnetic/	●			●		
	Volcano Above the Clouds* Tuesday, Nov. 25 • www.pbs.org/nova/kilimanjaro/	●		●			
	Orchid Hunter* (R) Tuesday, Dec. 9 • www.pbs.org/nova/orchid/			●			
	Wright Brothers' Flying Machine* (R) Tuesday, Dec. 16 • www.pbs.org/nova/wright/				●	●	
	Sinking City of Venice* (R) Tuesday, Dec. 23 • www.pbs.org/nova/venice/		●			●	
	Spies That Fly* (R) Tuesday, Dec. 30 • www.pbs.org/nova/spiesfly/		●			●	
40	**Ordering Information**						

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We're Moving to the Web!

This is the final printed version of the *NOVA Teacher's Guide*, which includes lessons for "Infinite Secrets" and "The Elegant Universe." Find all other lessons for the fall season, and all upcoming seasons, online at **www.pbs.org/nova/teachers/**

Read more about our move to the Web on page 3.

Because of schedule changes, some NOVA programs do not have lessons.

- one-year off-air taping rights
- seven-day off-air taping rights
- (R) repeat program
- lesson within this guide
- lesson online at: www.pbs.org/nova/teachers/

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Celebrating 30 Years of NOVA

Dear Educator,

This year NOVA turns 30, and it has been our great privilege almost since the very beginning of the series to serve educators by providing free, authoritative teacher's guides to accompany NOVA programming.

This year also marks a transition to the digital world for our educational outreach. This guide, which includes lesson plans for "The Elegant Universe," a three-part special on string theory, and "Infinite Secrets," a compelling biography about Archimedes, will be our final printed version.

We will now be providing all of our educational materials on the Web. Doing this allows us to offer you many critical improvements:

- a classroom activity for every new program
- easy links to related Web resources
- handouts that can be easily modified for your classroom needs
- accurate and up-to-date broadcast information
- an archive of the chapter-segmented programs and video clips that can be viewed online
- weekly e-mail broadcast reminders for those who sign up
- a careers-in-science section coming next year for your students to explore

Ultimately, we believe this transition will allow us to reach more teachers with more content. We have been grateful for all the positive feedback that we have received from educators over the years for the printed teacher's guide. As we embark on this new era, we want to hear from you—let us know if you have any problems with our new site or ways we can improve it. You can e-mail your ideas and comments to **NOVA_Teachers@wgbh.org**

We look forward to continuing working with you to provide ideas, resources, and support to help you engage today's youth in the excitement of science.

Sincerely,

Paula S. Apsell

Paula S. Apsell
Executive Producer

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Teacher's Guide Moves to the Web

We're moving our *NOVA Teacher's Guide* to a Web-only format, where we will be able to offer you easy access to our archive of more than 200 classroom activities, html and PDF versions of our new teacher's guides, and a complete listing of each season's upcoming NOVA programs. Our expanded online guide includes links to related NOVA resources to enhance your teaching, such as articles, interviews, and video and slide shows. Plus, we've created quick links to interactive activities that students can do online.

Each week we will add new classroom activities, interactives for students, and other resources to our ever-growing collection of materials. We hope you'll come back to visit often and would love to hear how the new site works for you. Please contact us through the site or e-mail us at **NOVA_Teachers@wgbh.org**

To stay informed of what's coming up on NOVA, sign up for our weekly e-mail bulletin. Each week you will receive a brief message about what's next in our broadcast schedule. All you have to do is type in your e-mail address at **www.pbs.org/nova/teachers/mailing/**

NOVA Teachers Home Page

Find out what's coming up on NOVA this season, the classroom activities we've developed to accompany our videos, how to receive brief notices of upcoming programs, and move through our site's home page.

TV Schedule

Get a complete listing of new and repeat NOVA programs coming up in the next several months, with subject area designations and links to program descriptions and printable classroom activities.

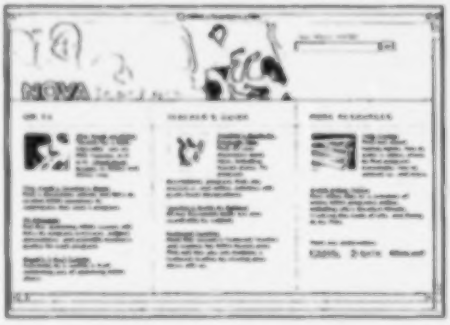
Teacher's Guide by Program Title

Search all of our resources by program title. Or use our Teacher's Guide by Subject page to find classroom activities, interactives for students, and other related resources in your area of interest.

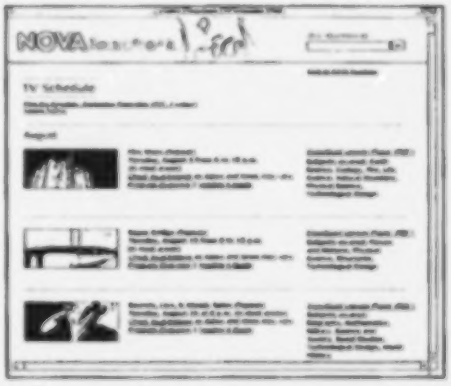
Classroom Activity

Each new activity includes an objective, materials list, student handout, procedure, activity answer, books and links, and alignment to math and science standards.

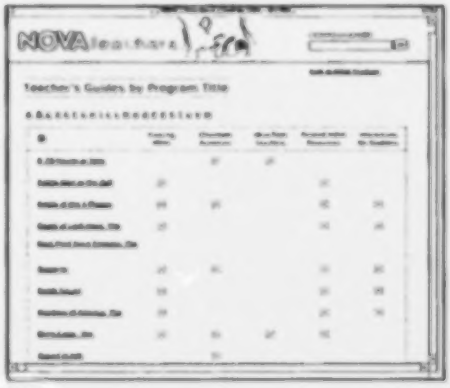
Home Page



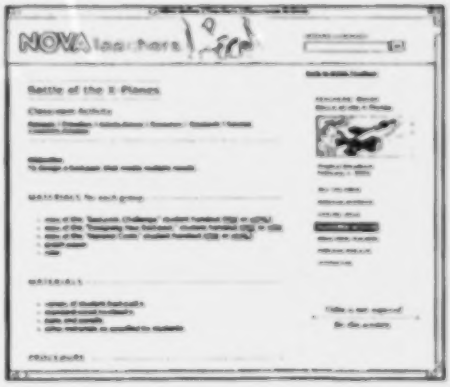
TV Schedule



Guides by Program Title



Classroom Activity



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Program Overview

NOVA explores the ongoing efforts of scientists to restore the 2,000-year-old Archimedes Palimpsest.

The program:

- defines a palimpsest: a manuscript in which the original text has been erased and the pages written on again.
- describes the discovery of the Palimpsest and its importance as a text that contains Archimedes' previously unknown mathematical treatises and illustrates Archimedes' process of discovery.
- explores Archimedes' life and some of his inventions, including his weapons of war.
- relates how Archimedes has become famous as the man who shouted "Eureka!" in the bath when he determined how to measure volume through water displacement.
- documents Archimedes' prowess as a mathematician by providing examples of some of his key ideas, such as his methods for determining the volume of an object and estimating the value of pi, his discoveries of complex mathematical shapes and the concept of buoyancy, and his work with infinity.
- chronicles the history of the manuscript from Archimedes' time to the present and details how the Palimpsest was created—12th-century monks in possession of the book erased the earlier recordings of Archimedes' work and reused the pages for a prayer book.
- illustrates how scientists are revealing the manuscript's concealed treasures.
- concludes with speculation about how much further the study of mathematics might be if the manuscript had not been lost for a millennium.

Before Watching

1. Archimedes made a number of mathematical and scientific discoveries during his lifetime. As they watch, have students take notes on Archimedes' key discoveries, how he made those discoveries, and the importance of each discovery.
2. Develop a timeline of important mathematicians, including those from non-Western civilizations such as Egypt, China, India, and Mesoamerica. Have students research the time and place where each mathematician lived and the contribution he or she made to mathematics. Develop a class timeline and add Archimedes to place him in the historical context of other mathematicians.
3. Ask students how math is important in their everyday lives. Have them give examples of how they use it or how their parents use it *(such as baking cookies, paying bills, building an object, or planning a garden)*.

Scientists are revealing the Palimpsest's concealed treasures with the aid of ultraviolet light and digital imaging.

After Watching

1. Have students refer to the notes they took about Archimedes' scientific and mathematical contributions. What were some of his inventions? Which of his discoveries were the most revolutionary and why?
2. An anonymous collector paid $2 million for Archimedes' Palimpsest *(a palimpsest is a manuscript that has been written on more than once)*. Discuss with students what makes the book so valuable. How was it created? How was it analyzed when first found in 1906? How is it being analyzed today? What was the effect of losing the manuscript for so long?

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Activity Setup

Objective

To duplicate the method Archimedes used to estimate the value of pi.

Materials for each group

- copy of the *Archimedes' Recipe for Pi* activity sheet on page 6
- paper
- pencil
- compass
- ruler
- calculator

Procedure

1. Tell students that they will be exploring Archimedes' method for estimating the value of pi, a mathematical constant that is the ratio of a circle's circumference *(the distance around a circle)* to its diameter *(the distance across a circle through its center)*. The Greek symbol for pi is π.
2. Organize students into groups. Provide copies of the *Archimedes' Recipe for Pi* activity sheet and other materials to each group.
3. Define some terms for students: *perimeter, circumference, radius, diameter,* and *area*. (See *Activity Answer* on page 7 for more information.)
4. Demonstrate how to draw polygons that are inscribed in a circle and circumscribed around a circle:
   - Draw a circle on the blackboard.
   - Use a ruler to draw four lines that divide the circle into eight equal parts, extending the lines beyond the boundary of the circle.
   - Connect the points where the lines meet the inside of the circle to create an octagon.
   - Connect the lines around the outside of the circle to create another octagon that just touches the edge of the circle.
5. Point out that the perimeters of the polygons give approximate values for the circumference of the circle. Students can divide each polygon perimeter by the diameter of the circle to find an approximate value for pi. (If necessary, remind students that to find the perimeter of a regular polygon they can measure one side of a polygon and multiply that length by the number of sides.)
6. Have students complete the data table and find the approximate values of pi for each of the three suggested sets of polygons (square, octagon, and hexadecagon) described on the activity sheet.
7. When students have finished the activity, discuss their results using the questions on the activity sheet.
8. As an *extension*, have students develop fact sheets about pi.

Standards Connection

The activity on page 6 aligns with the following *Principles and Standards for School Mathematics*.

Grades 6–8

Mathematics Standard:
Geometry

Mathematics Standard:
Measurement

Grades 9–12

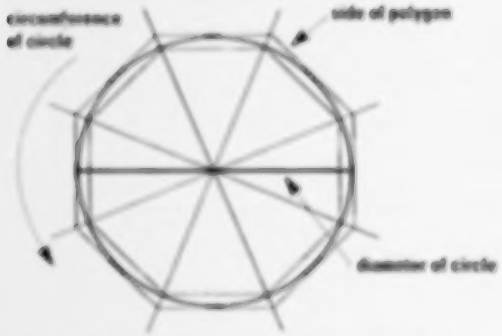
Mathematics Standard:
Geometry

Mathematics Standard:
Measurement

Archimedes' Recipe for Pi

NOVA Activity **Infinite Secrets**

One of Archimedes' many mathematical accomplishments was his computation of pi, which is the ratio of the circumference of a circle to its diameter. In this activity, you will duplicate the method he used to arrive at his estimate.



Procedure

1. Construct a data table on a separate piece of paper that contains the headings shown in the table below.
2. Use your compass to draw three circles on another piece of paper. Each circle can be a different size, but each should be at least 2 4 inches (6 centimeters) across.
3. Use a ruler to divide one circle into four equal pie-shape pieces. Be sure to extend your lines outside the circle. Then, using the ruler, create a square by drawing straight lines inside the circle to connect the points where the lines meet the circle.
4. Connect the lines around the outside of the circle to create a second square that just touches the circle's outside edge. Make sure that the straight line for each segment touches the circle at the segment's halfway point.
5. Measure one side of the inside square. Multiply that length by the number of sides in the square (four) to find the perimeter of the inside square. Record your results in the table. Repeat the process for the outside square.
6. Use the ruler to find the diameter of the circle and record this measurement.
7. The perimeters of the squares give approximate values for the circumference of the circle. Determine the value of pi by dividing the length of each perimeter by the diameter of the circle. Record your results for both the inside and outside squares.
8. Repeat the process for the second circle, using octagons (eight-sided polygons) instead of squares. Make eight equal pie-shape pieces. Then repeat the process again for the third circle, using hexadecagons (16-sided polygons).

Questions

Write your answers on a separate piece of paper.

1. The actual value of pi to four decimal places is 3.1415. Compare the range of values you found for each set of polygons to this number. Do all three ranges include the actual value of pi? Which type of polygon gave the most accurate range of values?
2. Archimedes calculated the value of pi for polygons containing 96 sides. Do you think his calculations were more or less accurate than yours? Explain.

Polygon Measurements

Polygon Name	# of Sides	Length of Side (in cm)		Perimeter of Polygon (= number of sides x length of 1 side)		Diameter of Circle (in cm)	Value of Pi (=perimeter/diameter)	
		inside polygon	outside polygon	inside polygon	outside polygon		inside polygon	outside polygon
Square	4							
Octagon	8							
Hexadecagon	16							

Activity Answer

Polygon Measurements: Sample Results

Polygon Name	# of Sides	Length of Side (in cm)		Perimeter of Polygon (= number of sides x length of 1 side)		Diameter of Circle (in cm)	Value of Pi (=perimeter/diameter)	
		inside polygon	outside polygon	inside polygon	outside polygon		inside polygon	outside polygon
Square	4	2.09	3.03	8.36	12.12	3.00	2.78	4.04
Octagon	8	1.14	1.25	9.12	10.00	3.00	3.04	3.33
Hexadecagon	16	0.58	0.61	9.28	9.76	3.00	3.09	3.25

If students need guidance, you may want to clarify the following concepts:

perimeter: the distance around a polygon; the perimeter is determined by the sum of the lengths of the sides of the polygon.
circumference: the distance around a circle; the circumference is the perimeter of a circle.
radius: any segment from the center of a circle to its edge.
diameter: any segment from one side of a circle to the other through the circle's center; the diameter is the same length as two radii.
area: the amount of space included within a polygon or circle.

For any circle, if you divide the circle's circumference by the diameter you will always get the same number, pi. Pi represents the ratio of the circumference of a circle to its diameter. Pi can be used to find the circumference and the area of a circle, if you know what the radius (*r*) of the circle is. The equations for determining those values are:

Circumference = $2 \times \pi \times r$
Area = $\pi \times r \times r$

The concept of pi has fascinated mathematicians for more than 4,000 years, ever since people first noticed that the ratio of circumference to diameter was the same for all circles, regardless of the circle's size. Although earlier estimates of the value of pi exist, Archimedes seems to have carried out the first theoretical calculation of the constant. His approach consisted of inscribing and circumscribing regular, many-sided polygons in and around the circle, and computing the perimeters of these polygons. This provided him with the approximation $223/71 < \pi < 22/7$, or $3.1408 < \pi < 3.1428$. (The actual value of pi to four decimal places is 3.1415.) Pi is an infinite decimal; its value is currently known to more than 1 trillion decimal places.

Archimedes did not have access to the modern-day tools of algebra, trigonometry, or even decimal notation. Instead, he performed his calculations using purely geometrical methods. Thus, constructing and calculating the values of the perimeters of 96-sided polygons, and then using these values to estimate pi, was by no means a trivial task.

Students' answers should reflect that Archimedes' method gives an approximate range of values for pi, with the value from the inside polygon providing the lower boundary and the value from the outside polygon providing the upper boundary. In addition, students should discover that the more sides a polygon has, the better approximation of pi it provides. This is because a polygon with many sides gives a better approximation of the circumference of the circle than one with fewer sides.

Students may wonder why it was so difficult to measure the circumference of a circle. The reason is that at the time Archimedes lived, there was no way to accurately measure curved lines—only straight lines could be measured. This is why Archimedes had to devise a way to approximate a circle's circumference.

Resources

Book

Stein, Sherman.
Archimedes: What Did He Do Besides Cry Eureka?
Washington, DC: The Mathematical Association of America, 1999.
Describes the life of Archimedes, the discovery of his manuscript in 1906, and his methods for figuring out many of the concepts he developed.

Web Site

Archimedes Home Page
www.mcs.drexel.edu/~crorres/Archimedes/contents.html
Includes information on Archimedes' life and work as well as illustrations of his inventions.

Find more resources in Links and Books online at **www.pbs.org/nova/archimedes/**

The Elegant Universe Teacher's Guide

It's the holy grail of physics—the search for the ultimate explanation of how the universe works. And in the past few years, excitement has grown among scientists in pursuit of a revolutionary approach to unify nature's four fundamental forces through a set of ideas known as superstring theory. NOVA unravels this intriguing theory in its three-part series "The Elegant Universe," based on physicist Brian Greene's best-selling book of the same name.

The first episode introduces string theory, traces human understanding of the universe from Newton's laws to quantum mechanics, and outlines the quest for and challenges of unification. The second episode traces the development of string theory and the Standard Model and details string theory's potential to bridge the gap between quantum mechanics and the general theory of relativity. The final episode explores what the universe might be like if string theory is correct and discusses experimental avenues for testing the theory. Throughout the series, scientists who have made advances in the field share personal stories, enabling viewers to experience the thrills and frustrations of physicists' search for the "theory of everything."

Program Host

Brian Greene, a physicist who has made string theory widely accessible to public audiences, hosts NOVA's three-part series "The Elegant Universe." A professor of physics and mathematics at Columbia University in New York, Greene received his undergraduate degree from Harvard University and his doctorate from Oxford University, where he was a Rhodes Scholar. His book *The Elegant Universe* was a Pulitzer Prize finalist in general nonfiction.

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See It on PBS

"The Elegant Universe" will air on the dates listed below. Check your local listings to confirm dates and times. The series can be taped and used for educational purposes for up to one year following the original broadcast.

Einstein's Dream
October 28, 2003, at 8 p.m.
String's the Thing
October 28, 2003, at 9 p.m.
Welcome to the 11th Dimension
November 4, 2003, at 8 p.m.

The series is available on video and DVD. Educators will receive a 50 percent discount on the series until July 1, 2005. Mention offer code TEG50 when you order by calling (800) 949-8670 or by visiting **shop.wgbh.org/**

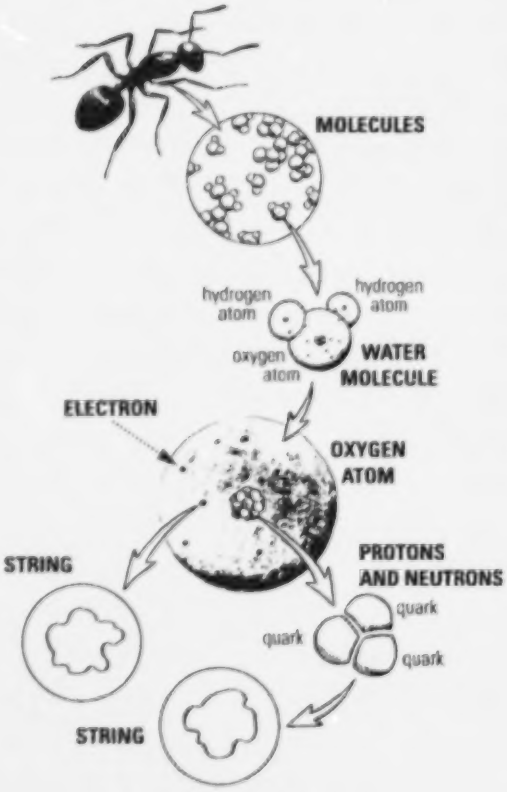
On the Web

NOVA has developed a companion Web site to accompany "The Elegant Universe." The site features interviews with string theorists, online activities to help clarify the concepts of this revolutionary theory, ways to view the program online, and more. Find it at **www.pbs.org/nova/elegant/**

About This Guide

Many aspects of string theory are abstract and difficult for even theoretical physicists to fully comprehend. The activities in this guide are designed to help you and your students better understand some of the basic concepts underlying particle physics and string theory. A list of additional resources and a glossary are included to help you gain further understanding of these fascinating, but complex, topics.

Each activity includes a teacher activity setup page with background information, an activity objective, a materials list, a procedure, and concluding remarks. Reproducible student pages are also provided. Most activities align with the *National Science Education Standards'* Physical Science standard, Structure of Atoms and Structure and Properties of Matter sections.



Some physicists believe that the most fundamental units currently known to make up matter—the electrons and the quarks that form protons and neutrons in atoms—may actually be made of tiny vibrating strings. Strings are almost unimaginably small—if an atom were enlarged to the size of the known universe, a string would only be about the height of a tree.

Particle Puzzle Pieces page 18

So far, the smallest constituents of matter confirmed by experiments are quarks and leptons. This activity acquaints students with the elementary particles of the Standard Model of particle physics by having them construct a proton and neutron from quarks. It is best suited for those students who have some understanding about elementary particles.

Forces of Nature page 21

Forces drive the interactions between elementary particles. Without the four fundamental forces the universe could not exist. In this activity, students learn about the four forces and the interactions they govern. Students who are acquainted with the four forces of nature will do best with this activity.

A New Building Block? page 25

Some theoretical physicists think that quarks and leptons are not the building blocks of the universe. Rather, they propose a new unit—a string. In this activity, students learn about this novel theoretical element and explore how a string's vibrational pattern determines which particle it is. Doing this activity requires a working knowledge of the relationship between energy and mass.

Deducting Dimensions page 28

In order for string theory to be valid, the universe must have an additional six or seven spatial dimensions. This activity helps students first visualize a universe with fewer than three spatial dimensions and then consider how more than three spatial dimensions may exist. This activity calls for visualization and creative thinking.

Detective Work page 31

No part of string theory has yet been supported with physical evidence. String theory proponents are hoping that current or next-generation particle accelerators and detectors will find evidence to support string theory's claims. In this activity, students learn how to interpret particle interactions captured by one type of detector, a bubble chamber. This activity will be most meaningful for students who have an understanding of the particle nature of matter.

The Science of Superstrings

Today's physicists are struggling with a quandary. They have accepted two separate theories that explain how the universe works: Albert Einstein's general theory of relativity, which describes the universe on a very large scale, and quantum mechanics, which describes the universe on a very small scale. Both of these theories have been supported overwhelmingly by experimental evidence.

Unfortunately, these theories don't complement one another. General relativity, which describes how gravity works, implies a smooth and flowing universe of warps and curves in the fabric of spacetime. Quantum mechanics—with its uncertainty principle—implies that on an infinitesimally small scale, the universe is a turbulent, chaotic place where events can only be predicted with probabilities. In two cases where the competing theories must both be applied—to describe the big bang and the depths of black holes—the equations break down.

Most physicists have a hard time accepting that the universe operates according to two separate (and sometimes contradictory) theories. They think it is more likely that the universe is governed by a single theory that explains all observations and data.

The Hunt for One Theory

For that reason, physicists are on the hunt for a unified theory. Such a theory would bring together under one umbrella all four forces of nature: gravity, the weakest of the four, as explained by general relativity; and electromagnetism and the strong and weak forces, as explained by quantum field theory. Einstein pursued a unified theory by trying to unite electromagnetism and gravity.

Superstring theory, also called string theory, is the current formulation of this ongoing quest. String theory attempts to unify all four forces, and in so doing, unify general relativity and quantum mechanics. At its core is a fairly simple idea—all particles are made of tiny vibrating strands of energy. (String theory gets its name from the string-like appearance of these energy strands.) Unlike everyday strings, these strings have length (averaging about 10^{-33} centimeters) but no thickness. String theory implies that the particles that comprise all the matter that you see in the universe—and all the forces that allow matter to interact—are made of tiny vibrating strands of energy.

The currently accepted and experimentally verified theory of how the universe works on subatomic scales holds that all matter is composed of—and interacts through—point particles. Known as the Standard Model, this theory describes the elementary particles and three of the four fundamental forces that serve as the building blocks for our world (see the *Elementary Particles* chart on page 18 and the *Fundamental Force Particles* chart on page 21 for a listing of these particles). This theory does not include gravity.

What Does "Fundamental" Mean?

Particle physicists sometimes use the word fundamental, or elementary, to describe the particles and forces found in the Standard Model. They are using this word to describe what they currently know are the most indivisible particles and the most basic forces in nature. But are these particles and forces really the most fundamental? The answer is that no one really knows.

In ancient times, people believed that nature's most fundamental elements were earth, water, air, and fire. In about 400 B.C. the Greek philospher Democritus conceived that matter was composed of little individual pieces, called *atomos*, which is Greek for uncuttable. Early in the 20th century, it was believed that neutrons and protons were the basic indivisible constituents of an atom's nucleus. Now it is thought that quarks and leptons are the most basic units possible. But if string theory is verified, strings will become the most fundamental units. Discovering the building blocks of nature is an evolutionary process. What was fundamental in the past no longer is, and what is considered fundamental today might not be tomorrow.

So when we say particles are fundamental, or elementary, throughout this text, we mean that these are the most indivisible building blocks of nature that we currently know of.

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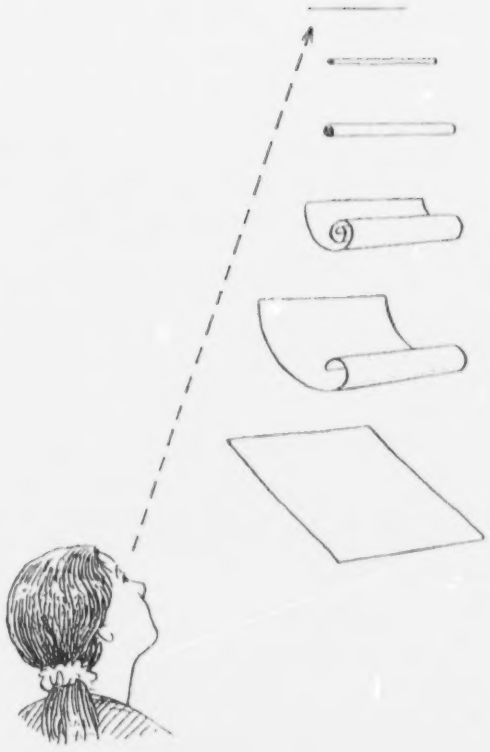
In string theory, each type of elementary matter particle—and each type of fundamental force carrier particle that mediates interactions between matter particles—corresponds to a unique string vibrational pattern, somewhat as different notes played by a violin correspond to unique string vibrations. How a string vibrates determines the properties—such as charge, mass, and spin—of the particle it is. The equations of string theory could give rise to elementary particles like those currently known (electrons, quarks, photons, etc.), but because detailed numerical predictions cannot yet be made, it is difficult to know whether the assortment of possible vibrational patterns correctly accounts for all known matter and force carrier particles. Strings can either be open-ended or closed to form a loop. Whether a string is open or closed determines the type of interactions it can undergo.

It is the nature of strings that unifies general relativity and quantum mechanics. Under quantum field theory, particles interact over zero distance in spacetime. Under the general theory of relativity, the theorized force carrier particle for gravity, the graviton, *cannot operate* at zero distance. Strings help solve this dilemma. Because they are one-dimensional and have length, they "smear" interactions over small distances. This smearing smooths out spacetime enough for the graviton to interact with other quantum field particles, thus unifying the two sets of laws.

A Hefty Price Tag

But string theory, for all its elegance, comes with a price. For the theory to be consistent, the universe must have more than three spatial dimensions. In fact, string theory predicts a universe with nine spatial and one time dimension, for a total of 10 dimensions. (The most current version of string theory predicts 11 dimensions.) The nine spatial dimensions consist of the three extended dimensions that we experience in everyday life, plus six theorized tiny, curled-up dimensions that can't be seen with existing technologies. These extra six dimensions occur at every point in the familiar three-dimensional world. The existence of more than three spatial dimensions is such a difficult concept to grasp that even string theorists cannot visualize it. They often use analogies to help picture these abstractions.

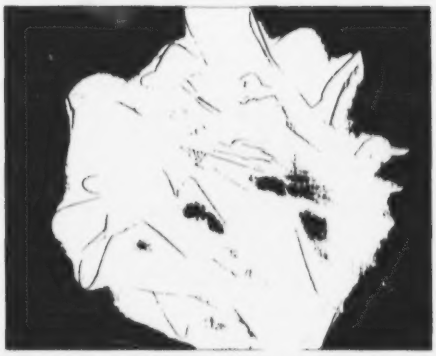
For example, picture a piece of paper with a two-dimensional, flat surface. If you roll up this surface, it will form a tube, and one dimension will become curled. Now imagine that you continue rolling the surface until it is rolled so tightly that the interior curled-up dimension seems to disappear and the tube simply looks like a line. In a similar manner, the extra dimensions predicted by string theory are so tightly curled that they seem to disappear in everyday experience.



If rolled up tightly enough and seen from a distance, a two-dimensional piece of paper can appear as a one-dimensional line, with the second—curled up—dimension hidden from view.

These curled-up dimensions may take on certain complex configurations known as Calabi-Yau shapes. Unfortunately, tens of thousands of variations of these shapes exist, and it is difficult to know which ones might correctly represent the extra dimensions of our universe. It is important to know which ones are correct because it is the shape of these extra dimensions that determines the patterns of the string vibrations. These patterns, in turn, represent all the components that allow the known universe to exist.

These extra dimensions might be as small as 10^{-35} meters or as big as a tenth of a millimeter. Alternatively, the extra dimensions could be as large or larger than our own universe. If that's the case, some physicists believe gravity might be leaking across these extra dimensions, which could help explain why gravity is so weak compared to the other three forces.



Calabi-Yau shapes, such as the one in this computer model, are theorized to possibly contain string theory's added dimensions.

It's a Match

String theory also calls for every known matter particle to have an as-yet-undiscovered corresponding "super" force carrier particle and every known force carrier particle to have an as-yet-undiscovered corresponding "super" matter particle. This idea, known as supersymmetry, helps establish a relationship between matter particles and force carrier particles. Called superpartners (see *Particles and Sparticles* below), these theorized particles are thought to be more massive than their known counterparts, which may be why they have not yet been observed with current particle accelerators and detectors.

Matter Matters

The matter described in this guide refers to matter that consists of atoms. However, atomic matter only makes up 4 percent of the universe. The rest of the universe is composed of dark matter (23 percent) and dark energy (73 percent), an unseen force that appears to be causing the universe to speed up its expansion. Scientists are still searching for what might make up these dark mysteries of the universe.

Particles and Sparticles

Matter particles and their proposed superpartners		Force particles and their proposed superpartners	
Particle Name	**Superpartner Particle**	**Particle Name**	**Superpartner Particle**
Quark	Squark	Graviton*	Gravitino
Neutrino	Sneutrino	$W^{+/-}$	$Wino^{+/-}$
Electron	Selectron	Z^0	Zino
Muon	Smuon	Photon	Photino
Tau	Stau	Gluon	Gluino
		Higgs* boson	Higgsino

* The graviton and the Higgs boson have not yet been experimentally confirmed. Find a full listing of particles and their proposed superpartners in *Elementary Particles* at **www.pbs.org/nova/elegant/**

Glossary

Having trouble keeping all these terms straight? See the *Glossary* on page 38 for help.

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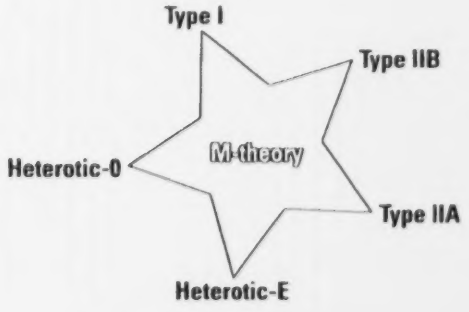
The potential for what string theory could help explain is huge. It could reveal what happened at the moment the universe began. The big bang theory only describes what happened after the first extremely small fraction of a second. Under conventional theories, prior to that the universe shrank to zero size—an impossibility. Under the auspices of string theory, the universe may never have shrunk to a point at which it disappeared but rather may have *begun* at a miniscule size— the size of a single string.

String theory could also help reveal the nature of black holes, which, while predicted by general relativity, have never been fully explained at the quantum level. Using one type of string theory, physicists have mathematically described miniature massless black holes that—after undergoing changes in the geometry of string theory's extra dimensions—reappear as elementary particles with mass and charge. Some theorists now think that black holes and fundamental particles are identical and that their perceived differences reflect something akin to phase transitions, like liquid water transitioning into ice.

String theory also opens the door to different hypotheses about the evolution and nature of space and time, such as how the universe might have looked *before* the big bang or the ability of space to tear and repair itself or to undergo topological changes.

When It All Started

String theory is not entirely new. It has been evolving since the late 1960s. At one point, there were five variations of the theory. Then, in the mid-1990s a theory known as M-theory emerged that unified the five theories. M-theory is considered the latest step in string theory evolution (see *M-theory, Magic, Mystery, Mother?* on page 14).



The latest incarnation of string theory—M-theory—revealed that five earlier versions of string theory were just five different aspects of one theory.

What a String Looks Like (Mathematically, That Is)

Think of a string as a curve in space. Open strings have two ends like an ordinary piece of string, while closed strings have no ends, like a rubber band. Both kinds of strings are important in string theory. Open strings were proposed first and are the strings described here. Mathematically, a string is defined, or *parameterized*, by a parameter called σ, which varies from 0 to 1. The point $\sigma = 0$ labels one end of the string, and the point $\sigma = 1$ labels the other end. The point $\sigma = 1/2$ is the point halfway between the ends, and so forth.

To know how a string is positioned in space you have to know the spatial coordinates of each point on the string. For example, the X coordinate of the point σ is called $X(\sigma)$. Now the string can wiggle and move in space. This means that the coordinates of points on the string can change with time. In other words, X is really a function of both σ and time τ, $X(\sigma, \tau)$. The way a string moves through space is described by an equation that involves the partial derivatives of X with respect to σ and τ as follows:

$$\frac{\partial^2 X}{\partial \tau^2} - \frac{\partial^2 X}{\partial \sigma^2} = 0$$

There is an equation like the one above for each coordinate of the string. These equations describe the complicated wiggling and vibrating motions that a string can have.

Courtesy of Leonard Susskind, Stanford University, California

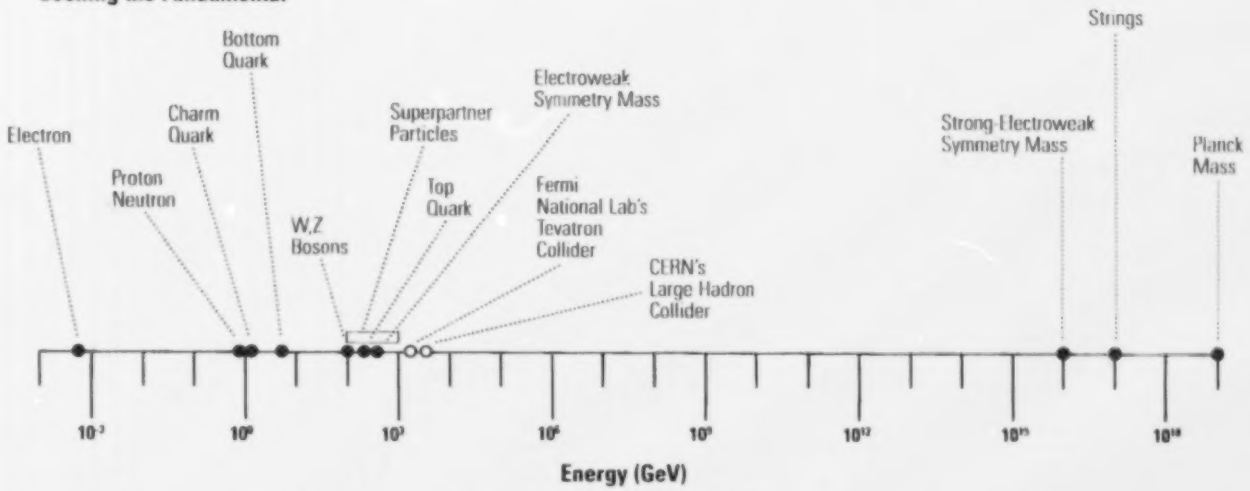
No part of string theory has been experimentally confirmed. This is in part because theoreticians do not yet understand the theory well enough to make definitive testable predictions. In addition, strings are thought to be so small—less than a billionth of a billionth of the size of an atom—that technologies such as current accelerators and detectors aren't powerful enough to detect them (see *Seeking the Fundamental* below). While string theory can't yet be experimentally verified, physicists hope that some of its facets can be supported by circumstantial evidence, such as demonstrating the existence of:

- **extra dimensions.** Physicists hope that current or future particle accelerators will be able to help indicate the existence of extra dimensions. Detectors might measure the missing energy that would have leaked from our dimensions into those extra dimensions, possibly providing evidence that these dimensions exist.
- **superpartner particles.** Researchers will use current and next-generation particle accelerators to search for the superpartner particles predicted by string theory.
- **fluctuations in background radiation.** The universe is permeated by uniform radiation of the very low temperature of 2.7 degrees Kelvin. This is believed to be left over from the original very high temperature of the big bang. Comparing the temperatures from different locations in the sky only about 1 degree apart, extremely small differences in temperature have been found (on the order of one hundred thousandth of a degree Kelvin). Scientists are looking for even smaller differences in temperature of a specific form that may be left over from the earliest moments of the big bang, when the energies needed to create strings may have been attained.

M-theory: Magic, Mystery, Mother?

M-theory is the latest incarnation of string theory. By adding another spatial dimension to the mix—thus creating a theory with 11 dimensions—M-theory reveals that the five different string theories are just different aspects of the same theory. But M-theory adds a new layer to the theory—it says that strings may not be the only fundamental elements in nature. There may also exist things called membranes (or "branes" for short), which are just as fundamental. The difference between membranes and strings is that membranes are higher-dimensional objects than strings (strings are one-dimensional). Some theorists think that we live in a "three-brane" universe that is moving through higher-dimensional spacetime. Physicist Edward Witten, who first proposed the theory and named it, has never stated exactly what the M stands for; some conjectures have included *magic*, *mystery*, *membrane*, *matrix*, or *mother*.

Seeking the Fundamental



While physicists using colliders have found evidence for most of the matter and force particles that comprise the Standard Model, they are still seeking a theorized force carrier particle called the Higgs boson. This graphic shows the energies at which some particles and force unifications have been found or theorized (●) and indicates the energies that can be probed with current or planned colliders (○). Physicists hope that CERN's Large Hadron Collider in Switzerland and France—scheduled to go online in 2007—might reveal evidence of the Higgs boson, as well as indications of the theorized graviton and the elusive superpartner particles. Unifying the strong and electroweak forces or finding theorized strings appears to require probing energies far beyond what current technologies offer. Some theorists, however, believe that the string energy may be closer to current or planned accelerator energies.

The Elegant Universe

Einstein's Dream

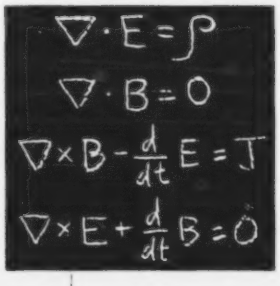
Airs Tuesday, October 28, 2003

Program Overview

NOVA introduces string theory and Albert Einstein's dream of unifying the forces that underlie all phenomena in the physical universe.

The program:

- reviews the quest for unification, the search for a single theory that describes all the laws in the known universe.
- introduces string theory as a candidate for a unified theory and summarizes the theory's main idea—that all matter and forces are made of tiny strands of energy that vibrate in different patterns.
- chronicles how, in 1665, Isaac Newton integrated the laws governing the heavens and Earth under the theory of gravity.
- details Einstein's discovery that nothing can travel faster than the speed of light and reveals how that finding conflicted with Newton's laws that showed that gravity acts instantaneously across any distance.
- explains how Einstein resolved the conflict with Newton's ideas by showing in his general theory of relativity that gravity travels at the speed of light.
- describes how electricity and magnetism were unified in the mid-1800s into a single theory of electromagnetism and illustrates how electromagnetism works and why it is hundreds of billions of times stronger than gravity.
- chronicles Einstein's quest to unite electromagnetism with gravity.
- relates the rise of subatomic physics in the 1920s and reviews the development of the radical theory of quantum mechanics and the uncertainty that rules the quantum world.
- conveys the discovery in the 1930s of two additional forces—the strong force and the weak force—and the eventual grouping of electromagnetism and the strong and weak forces under the umbrella of quantum mechanics.
- discusses the challenge of unifying the force of gravity with the forces described by quantum mechanics and expresses the need for a unified theory to describe phenomena in the universe, such as the depths of a black hole, which is both enormously massive and incredibly tiny.
- concludes with the idea that while string theory could unify general relativity and quantum mechanics, there is currently no way of experimentally confirming its predictions.



James Clerk Maxwell developed a set of four equations that unified electricity and magnetism into a single force known as electromagnetism.

Before Watching

1. Organize students into four groups. Assign each group one of the following concepts to research: 1) *four fundamental forces (gravity, electromagnetism, strong force, weak force)*, 2) *quantum mechanics*, 3) *unified theory*, and 4) *string theory*. (See *Resources*, pages 36–37.) Have each group create a poster explaining the concept and present its work to the class. Post each group's work for later reference. As they watch, have students take notes on their assigned topics.
2. Discuss the concept of *gravity*. Ask students to describe how they experience the force directly. Ask them how gravity affects objects beyond Earth.

After Watching

1. Review students' notes from the program. Have students update their posters with the new information they have learned. When and how was each force discovered? What additional questions do students have about each of the forces?

Glossary

Having trouble keeping all these terms straight? See the *Glossary* on page 38 for help.

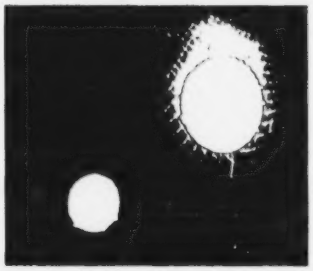
The Elegant Universe

String's the Thing

Airs Tuesday, October 28, 2003

Program Overview

NOVA explores the evolution and features of string theory.



The smooth, gently curving image of space predicted by the laws of general relativity is only half the story—at subatomic levels, space is bumpy and chaotic.

The program:

- reviews the concepts of general relativity (Einstein's theory of gravity that describes the universe on a large scale) and quantum mechanics (a theory that describes the universe on a very small scale) and the conflict between the two.
- discusses the breakdown of general relativity and quantum mechanics at the moment of the big bang, when the universe was both enormously massive and incredibly tiny.
- suggests that string theory may be able to unite the theories of general relativity and quantum mechanics, which would combine the four forces of nature—gravity, electromagnetism, the strong force, and the weak force—under one theory.
- describes the particles that comprise matter and relates how string theory proposes that the most elementary subatomic particles currently known may be made of strings.
- introduces the criticism that string theory cannot currently be tested experimentally or confirmed observationally.
- chronicles the development of string theory, including the theory's problems with mathematical inconsistencies, extra dimensions, and its prediction of an as-yet-unobserved massless particle (later theorized to be the graviton).
- reviews the development of the Standard Model, the experimentally verified theory that details elementary particles and their interactions, but does not include gravity.
- details the discovery of particles that carry the electromagnetic, the strong, and the weak forces and reviews the idea that these forces may have been unified at the earliest moments in time.
- explains how string theory evolved to provide a framework for understanding the four fundamental forces.
- reviews the basic concepts of string theory and how it resolves the conflict between general relativity and quantum theory.
- explains what dimensions are, explores the idea that string theory requires a universe with more than four spacetime dimensions, and proposes where these dimensions may exist.
- discusses the importance of the shape of the extra dimensions in determining the precise values of the fundamental components of the universe.
- highlights the dilemma string theorists faced in the late-1980s—that while searching for one theory of everything, they arrived at five different mathematically consistent, equally valid string theories.

Before Watching

1. Review with students the concepts for which they created posters for Episode 1 *(four fundamental forces, quantum mechanics, unified theory,* and *string theory).* Organize students into four new groups to create informational posters for display on the following concepts: *general theory of relativity, big bang, Standard Model,* and *extra dimensions.* Display these with the previous posters students created.

After Watching

1. Ask students to explain how string theory differs from the Standard Model. What are the main differences between the two?
2. Discuss the nature and process of science *(e.g., that theories be testable and that experiments produce repeatable results).* Does string theory fall under the realm of physics or philosophy? Have students debate the advantages and disadvantages of pursuing a theory that cannot presently be tested experimentally. How will string theorists ever know whether the theory is correct?

Welcome to the 11th Dimension

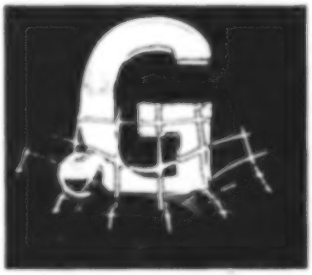
Airs Tuesday, November 4, 2003

Program Overview

NOVA explores some questions that string theory may be able to answer about the nature of the universe.

The program:

- explores the idea of wormholes, tube-like tunnels through the fabric of space.
- relates how string theory resolves the conflict between a spatial fabric that can deform but not tear (as described by the general theory of relativity) and space that may tear (in accordance with the concepts of quantum mechanics).
- reviews the development of string theory.
- recalls the introduction of M-theory in 1995, a theory that unified five earlier versions of string theory into one theory.
- relates how M-theory calls for a universe with 11 spacetime dimensions, which is one more dimension than was proposed by previous string theories.
- suggests ways to envision the concept of extra dimensions, such as imagining a world of fewer dimensions, like the two-dimensional world of a movie.
- illustrates how the additional dimension of M-theory allows a string to stretch out into a membrane-like form that could exist in multiple dimensions.
- explains how the existence of membranes might allow for the presence of parallel universes that could exist inside the extra dimensions of M-Theory.
- speculates that additional dimensions might also help explain why gravity is much weaker than the other three forces—because it might be "leaking" into higher dimensions.
- discusses the incomplete nature of the big bang theory and relates how some scientists have tried to use string theory to explain the birth of the universe.
- relates how scientists are trying to find evidence of extra dimensions and supersymmetry to support string theory's predictions.



One of the questions that string theory is seeking to answer is why gravity appears so weak compared to electromagnetism, the strong force, and the weak force.

Before Watching

1. Organize students into five groups. As they watch, have each group take notes on one of the following concepts: *wormhole, M-theory, membranes, parallel universes,* and *extra dimensions.*
2. Ask students to describe the dimensions they experience. Ask them to give examples of two-dimensional representations of three-dimensional objects *(e.g., movies, photographs, and maps).*

After Watching

1. Review with students the notes they took on their assigned topics. What did students learn about each of these concepts? What questions remain? How might they find answers to questions they still have?
2. Much of string theory may sound to students like science fiction. Ask your students to think of examples of scientific ideas from the past that seemed improbable in their day *(e.g., Earth being round, the sun being at the center of the solar system, continental plate movement, landing a man on the Moon).* What led people to change their thinking about these ideas? What are some current ideas in science that seem improbable?

Particle Puzzle Pieces

Activity Setup

Objective

To learn about some of the elementary particles in the Standard Model by building a proton and neutron from quarks.

Materials for each team

- copy of the *Particle Puzzle Pieces* activity sheet on page 19

Procedure

1. Organize students into teams and distribute copies of the *Particle Puzzle Pieces* activity sheet.
2. Review with students the history and nature of the atom (for sources of information, see *General Physics Resources* on page 36). Then discuss with students the matter particles that make up the Standard Model (see *Elementary Particles* and *Elementary Antiparticles* below). Emphasize that all matter comprised of Standard Model particles is made from first generation particles (the instability of second and third generation particles causes them to quickly decay into stable first generation particles). Additionally, antimatter is rarely seen in the everyday world. (See *Activity Answer* on page 20 for more information.)
3. Have students use the *Quark Chart* and *Quark Recipe Rules* on their activity sheet to discover how to build a proton and a neutron.
4. Discuss students' results and answers to the questions on the activity sheet. To supplement this activity, have students use the *Atom Builder* to build a carbon atom out of elementary particles. Find it at **www.pbs.org/aso/tryit/atom/**

Elementary Particles

	Charge	1st generation particle	2nd generation particle	3rd generation particle
Quarks	+2/3	u up	c charm	t top
	-1/3	d down	s strange	b bottom
Leptons	0	ν_e electron-neutrino	ν_μ muon-neutrino	ν_τ tau-neutrino
	-1	e^- electron	μ muon	τ tau

Elementary Antiparticles

	Charge	1st generation antiparticle	2nd generation antiparticle	3rd generation antiparticle
Quarks	-2/3	$\bar{u}$ up antiquark	$\bar{c}$ charm antiquark	$\bar{t}$ top antiquark
	+1/3	$\bar{d}$ down antiquark	$\bar{s}$ strange antiquark	$\bar{b}$ bottom antiquark
Leptons	0	$\bar{\nu}_e$ anti-electron neutrino	$\bar{\nu}_\mu$ anti-muon-neutrino	$\bar{\nu}_\tau$ anti-tau-neutrino
	+1	e^+ positron	$\bar{\mu}$ anti-muon	$\bar{\tau}$ anti-tau

Background

The building blocks of matter that have been experimentally verified are the quarks and leptons described by the Standard Model. Since the discovery of the electron in 1897, physicists have identified some 200 subatomic particles, all of which are leptons or quarks or a combination of quarks. In this activity, students will investigate the "recipes" for constructing a proton and neutron from the quarks described in the Standard Model.

In Conclusion

Physicists have used particle accelerators and detectors to confirm the existence of most of the elementary particles and antiparticles predicted by the Standard Model. One particle that has been theorized but not yet discovered is called the Higgs boson. This particle is thought to be a force carrier particle linked with the Higgs field, which might be the mechanism by which particles acquire their mass. In the 1960s, the physicist Peter Higgs postulated the existence of this field through which all particles are thought to move. The Higgs boson is considered to be the final missing piece of the Standard Model.

Particle Puzzle Pieces

NOVA Activity **The Elegant Universe**

Have you ever wondered what you are made of? How about the chair you are sitting on? Or the soda you drink? Or the stars you see at night? After many experiments, physicists have found evidence that most of the matter you see around you is made from elementary particles called quarks. How do these particles form both you and your chair? Do this activity to find out.

Procedure

(1) You, your chair, and everything you can see are made of atoms. Atoms, in turn, are composed of protons, neutrons, and electrons. According to the well-tested Standard Model of particle physics, electrons aren't made of anything else, but protons and neutrons are made of particles called quarks.

(2) To find out how quarks make up a proton or a neutron, read the *Quark Chart* below and *Quark Recipe Rules* at the top of the next column. Then try to write a "recipe" to construct a proton and a neutron.

Questions

Write your answers on a separate sheet of paper.

(1) How are your quark recipes for a proton and a neutron alike? How are they different?

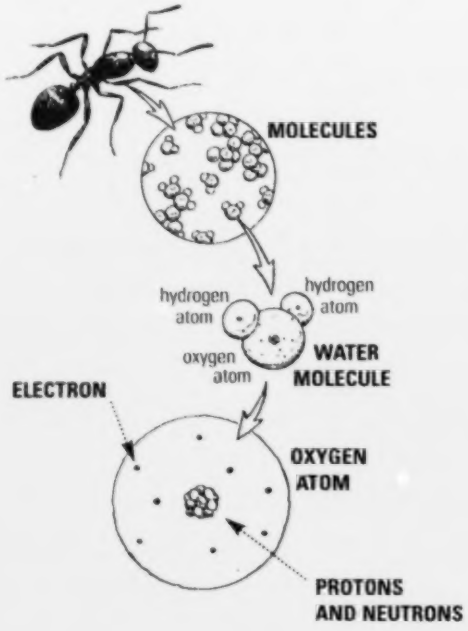
(2) Electrons are particles with a charge of -1 that can occupy the space around an atom's nucleus, which contains protons and neutrons. A neutral atom has a net charge of 0, which means that the number of negative electrons must equal the overall positive charge of the protons. How many electrons would you expect to find in a neutral atom containing three protons and four neutrons?

Quark Chart

Charge	1st generation particle	2nd generation particle	3rd generation particle
+2/3	u up quark	c charm quark	t top quark
-1/3	d down quark	s strange quark	b bottom quark
	less massive ⟶		more massive

Quark Recipe Rules

- More massive quarks are less stable than less massive quarks and quickly decay into less massive quarks. The quarks that make up protons and neutrons are all 1st generation quarks, which include up quarks and down quarks.
- Quarks never exist just by themselves. They are always found in the company of other quarks.
- Any particle made from quarks must have a net electric charge that is an integer (0, 1, etc.). Protons consist of a group of quarks with a combined charge of 1. Neutrons consist of a group of quarks with a combined charge of 0.
- Your recipe for a neutron or proton should use the smallest number of quarks that result in the correct charge.



Activity Answer

From the *Quark Recipe Rules*, students will likely infer that they should:

- only use 1st generation (up and down) quarks in their recipe.
- use more than one quark to build a proton and neutron.
- build a proton with a net integer charge of 1; and a neutron with 0 charge.
- use the smallest number of quarks possible to meet the stated criteria.

This information should help students discover through trial and error the composition of quarks necessary to describe a proton and a neutron: The proton should contain two up quarks and one down quark; the neutron should contain one up quark and two down quarks.

Check to ensure that student recipes use the lowest number of quarks possible—three. This concept is identical to that of the Least Common Multiple in mathematics. To create a neutral atom, three electrons would be needed in an atom containing three protons and four neutrons.

You may want to note to students that while antimatter particles are part of the basic building blocks in our universe, and have been identified by particle detectors, they are not observed very much in the everyday world. That's because when matter and antimatter meet, they annihilate each other. The resulting energy, however, is not lost; it can rematerialize as new particles and antiparticles.

Physicists theorize that at the time of the big bang, matter and antimatter were created in identical amounts. So why didn't the matter and antimatter annihilate each other and end the universe as we know it? Part of the answer may be that an asymmetry in the weak force occasionally converts antimatter into matter. But some physicists believe that this effect accounts for only some of the imbalance. New theories predict additional sources for asymmetry for which physicists continue to search.

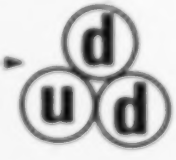
One of the few places where matter and antimatter occur outside of a particle accelerator is in the medical imaging technique known as Positron Emission Tomography (PET).

In PET, positrons (the antimatter partner of electrons) are created by the decay of radioactive nuclei. The process works by first attaching a radioactive element to a natural body substance (glucose is commonly used) and injecting it into a patient. After the targeted area absorbs the substance, the radioactive nuclei undergo beta plus decay and the positrons that are created collide almost immediately with the electrons they encounter. The mass of both particles is converted into two gamma rays that travel outward and away from each other in exact opposite directions.

Gamma ray detectors that surround the patient register and measure these events. After algorithms are applied to the data, an image is constructed that shows areas where radioactivity is concentrated. These areas indicate signs of metabolic activity, giving clues to where tumors are or providing information about physiologic function to help diagnose disease.

proton = +1 $+\frac{2}{3}$ $+\frac{2}{3}$ $-\frac{1}{3}$

neutron = 0 $+\frac{2}{3}$ $-\frac{1}{3}$ $-\frac{1}{3}$



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Web Connection
Find out more about elementary particles—such as their mass, charge, and spin properties—in *Elementary Particles* at **www.pbs.org/nova/elegant/**

Forces of Nature

Activity Setup

Objective

To learn about the four fundamental forces and the interactions they govern.

Materials for each team

- copy of the *Forces of Nature* activity sheet on page 22
- copy of the *Finding Forces* activity sheet on page 23

Procedure

1. Organize students into teams and distribute the *Forces of Nature* and *Finding Forces* activity sheets to each team.
2. Tell students that in order for the matter around them to exist in the way it does, the four fundamental forces are needed to mediate interactions between matter particles.
3. To help students understand the four fundamental forces, have them look at the *Finding Forces* activity sheet. Tell them that the areas of matter governed by the four forces are represented in the image. Explain to students that the interactions that affect matter particles are due to an exchange of particles called *force carrier particles*. Review each type of force carrier particle with students. Have students read the descriptions of the forces on their *Forces of Nature* activity sheet and work in teams to determine which area of matter each force governs. When they are done, have teams report their conclusions.
4. To conclude, discuss the forces, their relative strengths, and the force carrier particles that mediate interactions between elementary particles (see *Fundamental Force Particles* below for more information). Find more information about particles and their interactions at **particleadventure.org/particleadventure/frameless/chart.html**

Fundamental Force Particles

Force	Particles Experiencing	Force Carrier Particle	Range	Relative Strength*
Gravity acts between objects with mass	all particles with mass	graviton (not yet observed)	infinity	much weaker
Weak Force governs particle decay	quarks and leptons	W^+, W^-, Z^0 (W and Z)	short range	
Electromagnetism acts between electrically charged particles	electrically charged	γ (photon)	infinity	
Strong Force** binds quarks together	quarks and gluons	g (gluon)	short range	much stronger

* The relative strength of an interaction depends on the distance of separation of the particles. The strength continuum shown here is based on the separation between two protons in a nucleus.

** A secondary effect of the strong force—known as the residual strong force—binds together protons and neutrons, as experienced by hadrons, and is carried by mesons.

www.pbs.org/nova/elegant/

Background

Matter particles are only one part of the recipe for everything students see around them. The particles in matter must interact; otherwise the universe would just be one big collection of quarks and leptons. Particles, which undergo a number of interactions, are acted upon by four fundamental forces: gravity, electromagnetism, the strong force, and the weak force. In this activity, students will determine the interactions that are governed by each of these different forces.

In Conclusion

Matter particles and force carrier particles are part of the Standard Model, which provides a detailed catalog of many of the particles that comprise the universe. (The Standard Model does not include gravity.) All the particles predicted by the model have been detected except for the Higgs boson, the theorized force carrier particle associated with the Higgs field, which is believed to be what gives particles their mass. However, the Standard Model does not currently answer certain questions:

- Why is almost no antimatter observed?
- What makes up the dark, or unseen, matter that comprises a majority of the universe?
- How does gravity interact with the other three fundamental forces?
- Are there particles and forces still to be discovered?

Scientists are working to find a theory that helps answer these questions. Some physicists hope that string theory may eventually provide some of the answers.

Forces of Nature

NOVA Activity **The Elegant Universe**

The world is made up of elementary particles called *quarks*, which include the up, down, charm, strange, top, and bottom quarks; and *leptons*, which include the electron, the muon, the tau, and their corresponding neutrinos. But how do these particles interact? How do they form the world you see around you? Find out in this activity.

Procedure

① Look at the *Finding Forces* activity sheet. The graphic shows four areas of matter (labeled *1*, *2*, *3*, and *4*) that are governed by the four fundamental forces of nature.

② Read "The Four Fundamental Forces" section that starts below. Then see if you can match each force correctly with the numbers on the *Finding Forces* illustration. Write the letter of each description next to the number you think represents the area of matter governed by that force.

③ Once you have labeled the forces, write next to each force the name of the particle that carries (or is believed to carry) that force between the matter particles it governs. The force carrier particles are:

- **photon**
- **gluon**
- **graviton (theorized)**
- **W^-, W^+, Z^0**

The Four Fundamental Forces

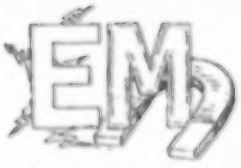
Ⓐ **Electromagnetism** causes like-charged objects to repel each other and oppositely charged objects to attract each other. The electromagnetic force binds negative electrons to the positive nuclei in atoms and underlies the interactions between atoms. Its force carrier particle is a photon.

Ⓑ The **strong force** binds quarks together. While the electromagnetic force works to repel the positively charged protons in the nucleus of an atom, the strong force is stronger and overrides these effects. The particle that carries the strong force is called a gluon, so-named because it so tightly "glues" quarks together into larger particles like protons and neutrons. The strong force is also responsible for binding protons and neutrons together in the nucleus.

gravity

strong force

weak force



electromagnetism

Ⓒ **Gravity** is the phenomenon by which massive bodies, such as planets and stars, are attracted to one another. The warps and curves in the fabric of space and time are a result of how these massive objects influence one another through gravity. Any object with mass exerts a gravitational pull on any other object with mass. You don't fly off Earth's surface because Earth has a gravitational pull on you. Gravity is thought to be carried by the graviton, though so far no one has found evidence for its existence.

Ⓓ The **weak force** is responsible for different types of particle decays, including a process called beta decay. This can occur when an atom's nucleus contains too many protons or too many neutrons—a neutron that turns into a proton undergoes beta minus decay; a proton that changes into a neutron experiences beta plus decay. This weak force is mediated by the electrically charged W^- and W^+ force carrier particles and the neutral Z^0 force carrier particle.

Questions

Write your answers on a separate sheet of paper.

① Which force is responsible for a neutron decaying into a proton?

② Which force bonds quarks together into particles like protons and neutrons?

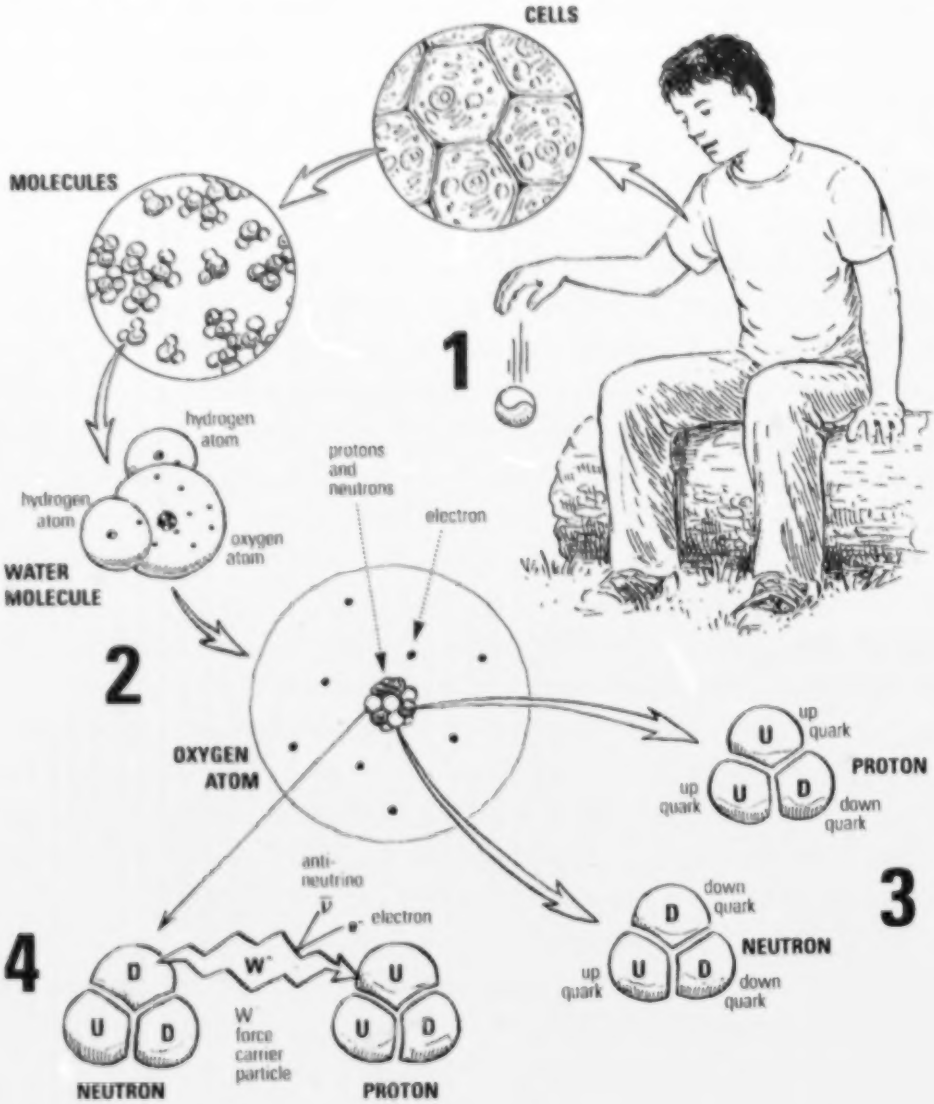
③ Which force governs the motion of an apple falling from a tree?

④ What are you made of? What forces hold you together?

Finding Forces

NOVA Activity **The Elegant Universe**

There are four fundamental forces that govern the interactions of matter. Read the descriptions of these on your *Forces of Nature* activity sheet (in "The Four Fundamental Forces" section) and assign the correct letter to the number on this page that represents the area of matter governed by that force.



Activity Answer

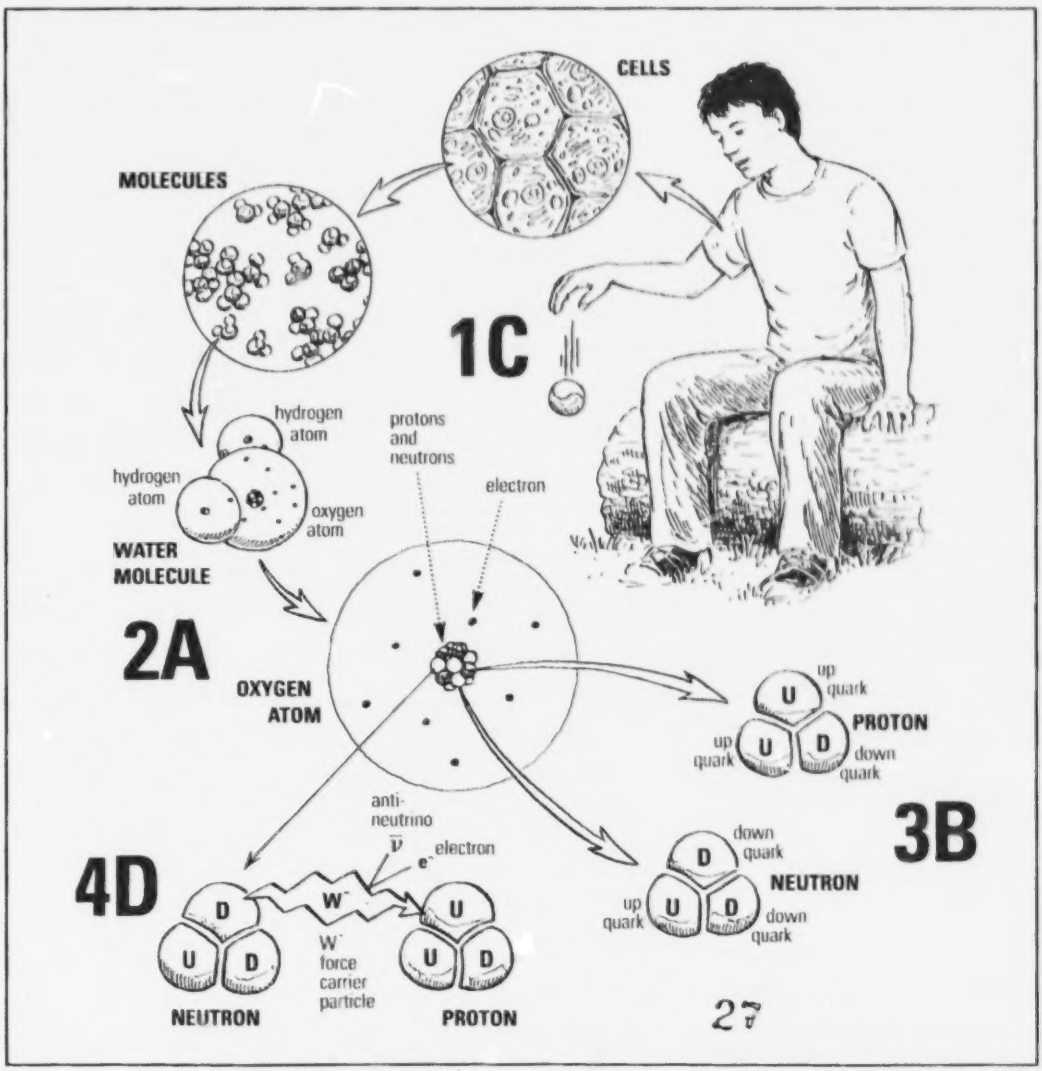
1 = C. **Gravity**
Theorized force carrier: graviton.

2 = A. **Electromagnetism**
Force carrier: photon.

3 = B. **Strong Force**
Force carrier: gluon.

4 = D. **Weak Force**
Force carrier: W^-, W^+, and Z^0.

The weak force governs the decay of a neutron into a proton (a process known as beta decay). The strong force binds quarks together into protons and neutrons (the residual strong force holds protons and neutrons together in the nucleus). Gravity governs the motion of an apple falling from a tree. Students are made of matter, which is organized into cells. Cells, in turn, are made of molecules, which are composed of atoms. Atoms are held together by electromagnetism (the residual electromagnetic force also binds atoms into molecules). On a more subatomic level, students are held together by the strong force that binds quarks into protons and neutrons and holds protons and neutrons together in an atom's nucleus.



A New Building Block?

Activity Setup

Objective

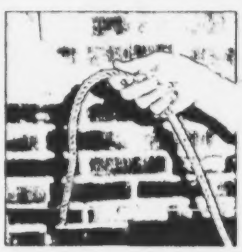
To learn about a new theoretical fundamental unit—a string—and explore how its vibrational pattern indicates the particle it is.

Materials for each group

- copy of the *A New Building Block?* activity sheet on page 26
- 15-foot-long rope (4.6 meters), 1/4- to 3/8-inch in diameter (6.3- to 9.5-millimeters)
- measuring tape, at least 15 feet (4.6 meters)
- clock or watch with a second hand
- calculator

Procedure

1. Share with students the idea that there may exist a subdivision of matter more fundamental than the currently confirmed quarks and leptons. This unit is called a string, and is thought by some to be the single building block of nature. Tell students that in this activity they will be exploring one feature of strings—that different patterns of string vibration correspond to the different matter and force particles that make up the universe they see around them.
2. Organize students into groups of four and distribute the *A New Building Block?* activity sheet and set of materials to each group.
3. Illustrate the process outlined on the activity sheet for finding the fundamental frequency. For the fundamental frequency, the rope twirler's arm motion will be circular, as if the twirler were playing jump rope. For the first overtone, a very small, rapid rotary hand motion will need to be applied, using just the wrist while keeping the twirling loop moving smoothly. It takes a bit of practice to achieve this.
4. Demonstrate the fundamental frequency using the circular motion. Then demonstrate the first overtone by speeding up the rotation. Do this by shifting to a rapid small hand motion, until the twisting loop splits into two twirling loops with a pinch point in the middle. (This pinch point is known as a *node*.) Explain that by using ever-faster hand motions, additional overtones of the fundamental frequency can be formed.
5. Have students do the trials and record their results through the second overtone. After this point it will be likely that students will not be able to twirl the rope fast enough to create a third overtone (up to a point, creating a third overtone is somewhat easier with a longer rope).
6. To close, point out that Einstein's famous equation, $E=mc^2$, indicates that mass can be viewed as a form of energy. Have students report which overtone required the most energy. Ask them to suggest which "strings," or overtones, might be more massive.



A 5/16-inch (8 millimeter) right-hand laid rope works well for this activity.

Choosing a Rope

When choosing a rope for this activity, look for one that will drape over your hand, not stick out stiffly. Thick, soft ropes like nylon tend to be easier to twirl than thin, stiff ropes like cotton clothesline.

Background

Some physicists think there is a unit of matter more fundamental than what has been experimentally confirmed to date. They think that everything in the universe is made of tiny vibrating strands of energy called strings. One feature of strings is that each one vibrates in a unique way, representing the mass, charge, and spin of known elementary particles. In this activity, students will use a rope to simulate a string's vibrational pattern and deduce the relationship between the mass of an elementary particle and the vibrational energy of its representative string.

In Conclusion

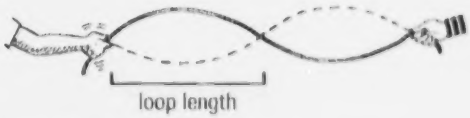
Although string vibration patterns give rise to the distinct elementary particles, strings are different from point particles in many ways. One of the most important differences is that strings are one-dimensional (unlike point particles, which have zero dimensions), which allows strings to behave in a way that permits the unification of the four forces. In addition, string theory offers a conceptual framework for answering questions such as why matter and force particles exhibit their observed properties. Present theories currently do not provide this information.

A New Building Block?

NOVA Activity **The Elegant Universe**

Some physicists think there is a unit of matter more fundamental than the particles that have so far been detected. They call this new building block a string (named for its string-like appearance). One of the key features of strings is that they generate different vibrational patterns that may give rise to the properties of currently known elementary particles. But how is it possible that elementary particles like electrons and top and bottom quarks—which have different masses—can be made out of the same thing? Do this activity to find out.

arm motion for the fundamental frequency



wrist motion for the first overtone

Procedure

① Organize your group into the following roles:
- rope holder
- rope measurer
- rope twirler
- timekeeper

② Have the rope holder grip the rope in a fixed position. For the first trial to determine the fundamental frequency, have the rope twirler use the type of arm action used to twirl a jump rope.

③ Once the rope is twirling smoothly, the measurer should measure and record the loop length. Then the twirler should call, "start," and the timekeeper should use a watch to time 30 twirls. The timekeeper should record this time. The frequency of the rope is defined as the number of twirls per second. Use your calculator to determine this number.

④ Repeat the above procedure and average the times for the two trials. This is the Fundamental Frequency. Record the loop length, time for 30 twirls, and frequency per second in the *Rope Resonance Chart*.

⑤ Now twirl the rope again, but this time the rope twirler should twirl the rope using his or her wrist only. The twirler should increase the speed of twirling until the large single loop breaks into two opposing loops turning around a mid-point, called a *node*. Once the two loops are twirling smoothly, measure the loop length and time 30 twirls as before. Do this twice and average the times. Record this result and the loop length under the First Overtone column.

⑥ Repeat this process for a rope that generates three equal loops and record your results in the chart.

Questions

Write your answers on a separate sheet of paper.

① What happened to the length of a single loop as you twirled faster?

② Review your data. What happened to the frequency as you twirled faster?

③ How did the change in loop length compare to the change in frequency as you twirled faster?

④ How did your effort change as you twirled faster?

⑤ Is there more energy in a higher overtone or a lower overtone? If a fundamental string was like your rope, would there be more energy in a rapidly vibrating string or a slowly vibrating string?

⑥ How might a string represent an elementary particle like an electron differently than a more massive elementary particle like a top quark?

Rope Resonance Chart

	Loop Length (Feet or Meters)	Time for 30 Twirls (Sec)	Frequency (Twirls/Second)
Fundamental Frequency			
First Overtone			
Second Overtone			

Activity Answer

As students twirl the rope faster and faster, the original loop breaks into first two, then three, smaller loops. These loops are separated by steady nodes.

Students may notice that as the loop length decreases, the frequency increases. As students twirl the rope faster, the frequency increases roughly proportionally to the overtone number. You may wish to have students pursue the reciprocal relationship between loop length and frequency.

Explain to students that the frequencies they produce in their trials are based on several factors—the length of the rope, the tension of the rope during the trial, and the mass per unit length of the rope. Different ropes will have different mass per unit length. Therefore, student results will most likely differ from the sample results in the chart on the right.

Students will find that it takes increasing effort to twirl the rope to higher overtones and from this they may surmise that rapidly vibrating strings are more energetic than more slowly vibrating strings. Einstein's famous equation $E=mc^2$ shows that mass is a form of energy. A more massive particle has more energy when sitting still than a less massive particle. This relationship explains how a single unit—a string—can account for particles of very different masses. A more massive top quark would correspond to a more energetic string (a higher overtone) than a less massive electron.

Rope Resonance Chart: Sample Results

	Loop Length (Feet or Meters)	Time for 30 Twirls (Sec)	Frequency (Twirls/Second)
Fundamental Frequency	L = 10 feet (3.0 meters)	17 seconds	30 twirls ÷ 17 sec = 1.76
First Overtone	L/2 = 5 feet (1.5 meters)	12 seconds	30 twirls ÷ 12 sec = 2.50
Second Overtone	L/3 = 3.3 feet (1.0 meters)	7 seconds	30 twirls ÷ 7 sec = 4.28

Web Connection

See how resonance affects both an everyday cotton string and the tiny strings of string theory in *Resonance in Strings* at **www.pbs.org/nova/elegant/**

Deducting Dimensions

Activity Setup

Objective

To visualize a universe with fewer than three spatial dimensions and to consider how more than three spatial dimensions could exist in the universe.

Materials for each team

- class copies of the *Deducting Dimensions* activity sheet on page 29

Materials for each student

- copy of the book *Flatland: A Romance of Many Dimensions* by Edwin A. Abbott (New York: Penguin Books, 1998); see original 1884 version at **nedwww.ipac.caltech.edu/level5/Abbott/Abbott_contents.html**

Procedure

1. Have students read parts or all of *Flatland* by Edwin Abbott, which provides an account of what life would be like in Flatland, where the inhabitants are all geometric shapes living in a two-dimensional world. This reading will give students an image of a universe with fewer dimensions. You may want to have students start at *Part 2: Other Worlds*, which describes the nature of one-, two-, and three-dimensional worlds.

2. Organize students into teams and distribute the *Deducting Dimensions* activity sheet.

3. Have teams record the answers to the five bulleted questions for the one- and two-dimensional universes they are imagining. Have teams also record any additional observations or realizations about these universes. Once they have finished, have teams answer the two questions listed on the activity sheet.

4. When students have completed the activity, have teams report their results. As students consider the perspectives of inhabitants in a world with fewer dimensions, discuss with them that these inhabitants would not likely be able to comprehend a three-dimensional world, even though one exists. Point out to students that just as the inhabitants of those universes would have difficulty picturing extra dimensions, so it could be for inhabitants of our world.

5. Discuss the idea of an additional six or seven spatial dimensions with students (different string theories assume a different number of added dimensions). Students may wonder where these extra dimensions are and why they cannot see them. Explain to students that some physicists believe these extra dimensions occur at every point in the universe but are extremely tiny and curled up. They are so tiny that they cannot be detected, even with the most sophisticated research equipment.

   To help students visualize this, you may want to have them imagine how various three-dimensional objects (such as a telephone cable or a clothesline) can seem at a distance like they are one-dimensional (a line that can be traversed back and forth). In these cases, two dimensions (side-to-side and up-down) appear hidden, just as the added six or seven dimensions in string theory appear hidden from view. (See page 11 for an illustration of this concept.)

Background

String theory is elegant in a number of ways: it accounts for both quantum mechanics and general relativity, it may have the potential to describe the elementary particles that make up matter and carry forces, and it provides a mechanism by which the four forces can be unified. For these reasons, supporters of string theory are willing to take on a daunting proposition—that the universe is not actually made up of the four commonly experienced spacetime dimensions, but may contain 10—perhaps even 11—spacetime dimensions. Without these additional spatial dimensions, the equations in string theory just don't work. This activity first calls for students to imagine a world of fewer dimensions before considering the idea of additional ones.

In Conclusion

Some physicists think that added spatial dimensions may take on incredibly complex forms known as Calabi-Yau shapes. *How* the dimensions are curled up, which physicists have not yet determined, may establish the properties of elementary particles. Taking a different tack, a few theoreticians propose that the extra dimensions may be very large, even infinite, but cannot be seen because all matter, as well as light, is trapped within the dimensions of our universe; matter from other universes would appear dark to us. In this theory, gravity is the only thing that escapes, leading some physicists to suggest that this would explain why gravity is by far the weakest of the four forces.

Deducting Dimensions

NOVA Activity **The Elegant Universe**

You experience daily life in three spatial dimensions (and one dimension of time). You move forward and backward, step left and right, and go up and down stairs as you move around your world. But string theory requires that you live in a world with an additional six or seven spatial dimensions. Without these extra dimensions, the equations in string theory don't make sense. But even physicists who think about these extra dimensions every day have a hard time picturing them. One way they improve their mental picturing ability is to work backward and imagine a world with *fewer* than three dimensions. See if you can imagine a universe with only one, and then two, dimensions.

3-D Chicken

2-D Chicken

1-D Chicken

Procedure

① To the right is a set of questions for each universe to get you started. See if you and your team members can answer the questions first for a one-dimensional universe and then for a two-dimensional universe.

② As you explore each universe, try to imagine what life would be like in that universe.

One-Dimensional Universe

This universe is like a line with no ends. It has no up and down or left and right, only a forward and backward that go on forever. Remember that it is not like a wire stretched across a room within a three-dimensional space. There is no outside room; wire is all there is, just forward and backward.

Two-Dimensional Universe

This universe is like a flat sheet of paper that goes on forever. Unlike the wire, this universe has a forward and backward and a left and right. What this universe does *not* have is an up and down.

Questions for each universe:

- What is the shape of a creature that inhabits the universe?
- How would one creature appear to another? If the creatures are able to move around one another, how would they appear to one another if they were lines? If they were rectangles? If they were circles?
- What path would a creature take as it moved?
- How could creatures communicate?
- What kind of social structures might exist?

Questions

Write your answers on a separate sheet of paper.

① How many creatures can a given creature communicate directly with in each universe, assuming that they must be in nearly direct contact with one another to do so?

② Suppose a message needs to be passed to 64 creatures. Assuming that one creature can only communicate with one other creature at a time and that each message takes one minute to transmit, what is the shortest amount of time that a message could be passed in a one-dimensional world? How would the transmission occur? What about in a two-dimensional world?

Activity Answer

In a one-dimensional universe:

- Creatures would have the form of a very thin worm, or a point-like dot.
- These creatures could not pass each other because that would require a second dimension. So one creature could only see the dot-like end of the next creature in front of or in back of it.
- These creatures could only move forward until they bumped into the creature in front of them and backward until they bumped into the creature behind them.
- These creatures could only pass messages from one to another down the creature line (like in the game "Telephone").
- Social structures would be limited to some number of inline-communicating creatures. There might only be one large group, or any number of smaller inline groups.

In a two-dimensional universe:

- Creatures could have any shape—such as a square, triangle, or circle—that is flat like a drawing.
- Creatures would have both length and width, but not height.
- One creature seeing another would see its companion as a line and discern the other creature's shape by viewing the other creature from various angles.
- Creatures could move in any direction in their flat universe, but because there is no up and down dimension, they would have to move around each other.
- As one creature moves around another, it could see the apparent length (or size) of the creature change (unless the other creature is circular).
- Any creature could pass a message to any other that it could move to.
- Any number of social structures would be possible: singles, tribes, or larger groups. The larger the group, the longer it would take to get a message from one creature to another.

Assuming that nearly direct contact is needed to communicate, in a one-dimensional world, a creature could only communicate with another creature that is either directly in front of or in back of it. In a two-dimensional world, if a creature is long and thin, it could arrange itself with others like it in a group like the spokes of a bicycle wheel so that any creature could communicate with any other across the center (see Figure 1).

Wider—or myriad long, thin creatures—could arrange themselves in a ring, but would have to pass messages from creature to creature around the ring. This loss of group contact would always occur at some number of members within a cluster. The narrower the creature, the more creatures that can remain in direct contact within a cluster.

In a one-dimensional world, the fastest way to communicate a message to 64 creatures would be for the creature in the middle first to tell the message to a creature on one side, and then to the creature on the other side. These creatures would then relay the message to the next two outside creatures, who would relay it to the creatures outside of them, and so on, down each side of the line. The process would take 32 minutes. In a two-dimensional world, the starting creature would transmit a message to a second creature. The first and second creature, then, would transmit a message to a third and fourth creature. Then all four creatures would transmit the message to four more creatures. This exponential transmission would continue for six minutes, at which time 64 creatures would have heard the message.

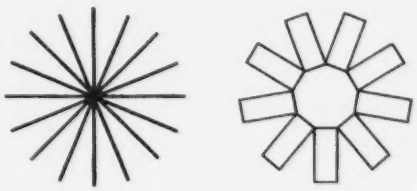


Figure 1. Narrow and wide creature clusters

Web Connection
Get some help in picturing a world of more than three dimensions in *Imagining Other Dimensions* at
www.pbs.org/nova/elegant/

Detective Work

Activity Setup

Objective

To learn how to interpret particle interactions captured in one type of detector, a bubble chamber.

Materials for each group

- copy of the *Sizing Up Protons* activity sheet on page 32
- copy of the *Bubble Chamber Basics* activity sheet on page 33
- copy of the *Tracking Particle Paths* activity sheet on page 34

Procedure

1. Tell students that particle physicists have learned much about the subatomic world through the use of particle accelerators—machines that speed up particles to very high speeds and either smash them into a fixed target or collide them together. Particles commonly used are protons, which contain quarks, and electrons and their antimatter counterparts, positrons. Various types of detectors record the results.This activity will acquaint students with one kind of detector, a bubble chamber.
2. Prior to having students analyze the bubble chamber image, acquaint students with subatomic dimensions by having them complete the *Sizing Up Protons* activity. Organize students into groups and distribute the *Sizing Up Protons* activity sheet to each group. Have students do the calculation and discuss the results.
3. After students have completed the scaling exercise, have them watch Fermilab's *Anatomy of a Detector* video clip (6 minutes, 13 seconds) that details how detectors work. Find it at **quarknet.fnal.gov/run2/boudreau.shtml**
4. Once they have watched the video clip, organize students back into groups and distribute a copy of the *Bubble Chamber Basics* and *Tracking Particle Paths* activity sheets to each group member. Tell students that the illustration represents some of the tracks that might be recorded by a bubble chamber detector. Inform students that bubble chambers are no longer used; physicists now use detectors that measure energies 1,000 times larger than bubble chambers can accommodate.
5. Have students read about how particle tracks are created on their *Tracking Particle Paths* activity sheets and answer the questions on the *Bubble Chamber Basics* activity sheet. If students are having difficulty you might want to assist them in identifying one of the tracks to help them get started. Check in with each group during the activity to answer students' questions or provide additional guidance. When students have finished the activity, clarify any questions remaining about the particle tracks. About which particles or interactions would students like to know more?
6. To conclude the lesson, ask students to give examples of other objects that cannot be "observed" without additional technologies *(e.g., atoms, bacteria, viruses, DNA, bones and soft-tissue organs in human bodies, oil deposits within the Earth)*. What are some technologies used to provide evidence for, or infer the existence of, these objects?

Background

One of the major criticisms of string theory is that it cannot presently be experimentally verified. Strings themselves—if they even exist—are thought to be much too small to detect using even the largest particle accelerators and detectors. It takes increasing amounts of energy to probe deeper into the basic constituents of matter. It takes more energy to break apart an atom's nucleus, for example, than it takes to break apart a molecule. The amount of energy it would take to find evidence of strings is believed by many physicists to be well out of reach of current particle accelerator technology (see *Seeking The Fundamental* on page 14). However, physicists are hoping that certain aspects of string theory can be confirmed with existing or planned accelerators and detectors or by other non-accelerator experiments. In this activity, students analyze a representation of particle tracks like those created in a bubble chamber, an early type of detector, to understand one way physicists studied objects they could not "see."

In Conclusion

Physicists hope that next-generation particle accelerators, such as the Large Hadron Collider (LHC) located in France and Switzerland, will provide evidence to support aspects of string theory. The LHC is scheduled to go online in 2007. One of the predictions of string theory is supersymmetry—the idea that every known elementary particle and force carrier particle has an as-yet-undiscovered partner particle, known as a superpartner. Future detectors may be able to record evidence of these superpartners. However, while such findings would support string theory, they would not necessarily confirm the theory—supersymmetry could be a feature of the universe even if string theory is not correct.

Sizing Up Protons

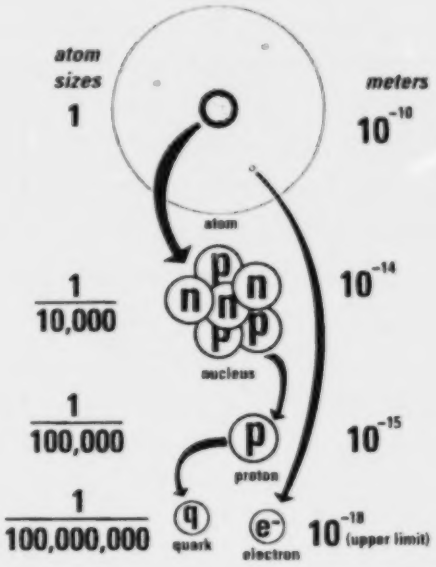
NOVA Activity **The Elegant Universe**

At one time, physicists used instruments called bubble chambers to detect what happened when they collided particles like protons together. But how big is a proton? In this activity, find out how big a proton would be if you scaled an atom to the diameter of Earth.

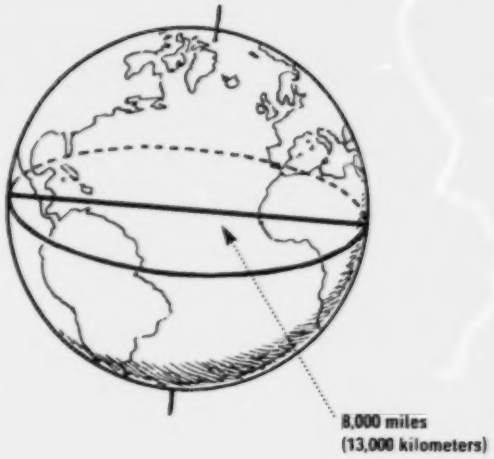
Colliding Protons

When physicists collided particles together in a bubble chamber, they were trying to produce new particles to study. One of the particles used in these collisions was the proton, a particle that, along with neutrons, makes up the nucleus of an atom. An atom's nucleus is much smaller than the whole atom, typically by a factor of 10,000. But how small is that? Read the following comparison of sizes and then do a calculation to find out just how small a proton is.

- Picture a circular pond with a diameter equal to the length of an Olympic swimming pool, which is about 165 feet (50 meters). If an atom were the size of this pond, the nucleus would be the size of a pencil eraser —1/5-inch diameter (about 5 millimeters)— floating in the middle of the pond.
- Inside a nucleus are neutrons and protons, which occupy a space about 100,000 times smaller than the whole atom. In the pond example, a proton would measure about 1/50th inch (0.5 millimeters) in diameter—about the size of a pinpoint.
- Given the information above, what would the diameter of a proton be if the diameter of an atom were as big as the diameter of Earth— about 8,000 miles (13,000 kilometers)? Once you have calculated how big the proton would be, find a visual analogy to represent that number. Is there anything around your home, school, or town that would be about the diameter of the proton if it were in an atom that was the diameter of Earth?



Source: The Particle Adventure
www.particleadventure.org/



Bubble Chamber Basics

NOVA Activity **The Elegant Universe**

Physicists once used a device called a bubble chamber to record particle interactions. The illustration on your *Tracking Particle Paths* activity sheet represents the kinds of particle interactions that were commonly recorded by bubble chamber detectors. Today, bubble chambers have been replaced by detectors that can measure energies a thousand times larger, and can look for particles a billion times more rare. However, bubble chamber tracks are useful to show the kinds of interactions that can occur between particles. Read the information in the *Tracking Particle Paths* activity sheet to learn more about bubble chambers and the kinds of tracks they produce. Then answer the questions below.

Questions

Write your answers on a separate sheet of paper.

1. Which letter(s) represent electron-positron pairs in this illustration? Which side of the pair(s) represents the electron? Which side represents the positron? Explain your answer.
2. Which track(s) show a Compton electron that has been knocked out of an atom? Explain.
3. Assuming that tracks C and D were formed by the same kind of particles and are the actual lengths shown, which pair had greater momentum? Explain.
4. Identify a track that did not come from the particle beam. How do you know? Where might this track have originated?
5. What might track F represent? Explain.
6. What were the main types of particle interactions recorded?
7. What particles would not leave tracks in a bubble chamber? How can you detect where unseen particles would have been in the illustration?

Tracking Particle Paths

NOVA Activity **The Elegant Universe**

Donald Glaser invented the bubble chamber in 1952. Inside the bubble chamber a superheated liquid, such as liquid hydrogen, is expanded just before particles are beamed through. The beamed particles—and some of the interactions they produce—ionize the atoms in the liquid, resulting in a series of bubbles along the trajectory of the particles. The bubbles make the tracks of the particles visible. The events are photographed. Once the events have occurred, the liquid is recompressed for the next particle burst. The following are some facts about how some tracks are formed:

- Only electrically charged particles leave trails. Protons, the particles beamed through the liquid in this example, are positively charged particles.
- Particles from outside the bubble chamber, such as cosmic rays, can also be recorded in the liquid.
- A magnetic field throughout the liquid in the chamber causes particle paths to bend. Particles with opposite charges produce paths that curve in opposite directions. In this representation, negatively charged particle trails curl left and positively charged particle trails curl right.
- The beamed particles all originated from the same direction and entered the liquid at the same speed.
- When a high-energy photon—which has no charge—interacts with a charged particle, the interaction can produce a pair of oppositely charged particles. This usually results in an electron-positron pair, a V-shaped trail in which each end of the V spins off in an opposite direction and spirals inward.
- Particles with less momentum, or those that have less mass, produce trails that curve more from the point *at which they were produced*. Particles with greater momentum, or those that are more massive, produce paths that curve less from the point of production. In the case of a particle pair, for example, a pair with greater momentum (or mass) will result in a longer, narrower V shape than a pair with less momentum (or mass).
- A photon that knocks an electron out of an atom creates a single track that bends to the left and spirals inward. This product is called a Compton electron.

Activity Answer

Sizing Up Protons

In an atom as big as Earth, a proton would be about 0.08 mile (130 meters) in diameter, close to the size of a running track around the outside of a typical football or soccer field. The equations for these results would be:

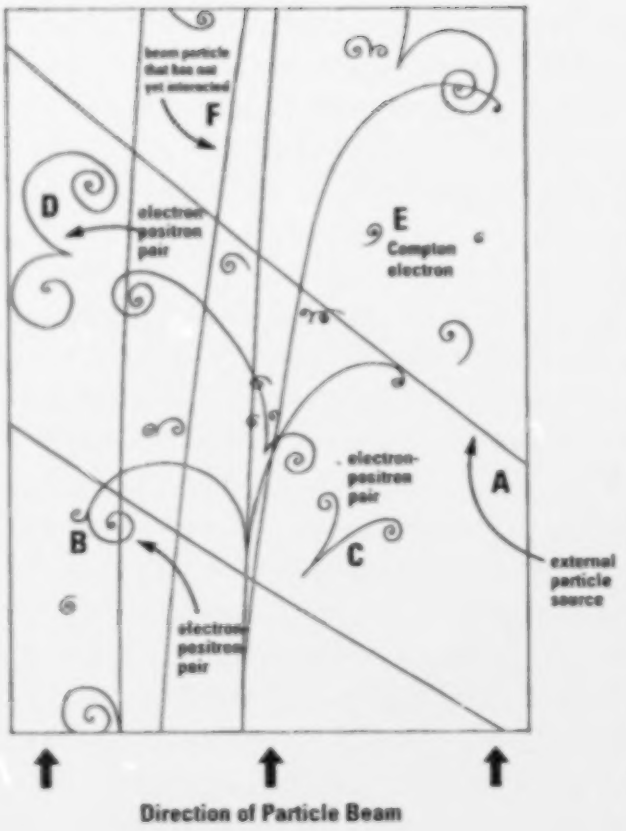
8,000 miles ÷ 100,000 = 0.08 miles
13,000 kilometers ÷ 100,000 = 0.13 kilometers (130 meters)

Tracking Particle Paths

The inward spiral track pattern created by electrons (and positrons) in the bubble chamber is due to the particles' energy loss. (An electron is a negatively charged particle while its anti-particle, called a positron, is positively charged.) Because electrons and positrons are much less massive than protons, they tend to accelerate more when experiencing an electromagnetic force. They lose their energy by ionizing the material in the bubble chamber. The bubbles form and grow on these ions, which creates the tracks that are photographed.

To the right is a correctly labeled version of the sample track illustration.

Tracks B, C, and D represent electron-positron pairs. Based on the direction of the magnetic field in this chamber, the electron is on the left side and the positron is on the right. Track E represents a Compton electron, which is created when a photon knocks an electron out of an atom. The particles at track C had greater momentum than the particles at track D, as indicated by track C being less curved than track D. (You may want to note to students that because particles in bubble chambers are interacting in three dimensions, the actual tracks created in the chamber might be longer than they appear in the recorded image.) Track A, which is entering from a different direction than the others, must have originated outside the detector. It was possibly produced by a cosmic ray. Track F represents a beamed proton that has not yet interacted with another particle, as indicated by its nearly straight path devoid of interactions. Compton electrons and electron-positron pairs were the main particle interactions recorded. Any particle that is electrically neutral, such as a neutrino or a photon, would lack the charge needed to leave a bubble track. These particles would be present where tracks suddenly appear or disappear.



Web Connection

Explore images from atom smashers that have captured particles in the act of being created or destroyed in *Atom Smashers* at **www.pbs.org/nova/elegant/**

Resources

General Physics

Books

Barnett, R. Michael, Henry Muehry, and Helen R. Quinn.
The Charm of Strange Quarks.
New York: Springer Verlag, 2000.
Reveals the concepts and discoveries of the Standard Model and related elements of cosmology. Includes explanatory drawings and photographs.

Gell-Mann, Murray
The Quark and the Jaguar.
New York: W.H. Freeman and Company, 1994.
Relates the author's search for the connections between the universe's fundamental laws and nature, in chapters that include the laws of physics and fundamental particles and selection pressures in complex systems.

Kane, Gordon.
The Particle Garden: Our Universe As Understood by Particle Physicists.
Reading, MA: Addison-Wesley, 1995.
Includes a history of particle physics, the Standard Model, and unification and explains the relation of particle physics to cosmology and astrophysics.

Schwarz, Cindy, and Sheldon Glashow.
A Tour of the Subatomic Zoo: A Guide to Particle Physics
Woodbury, NY: AIP, 1997.
Introduces the ideas, terminology, and techniques of high-energy physics and provides historical views of matter from the atom to the quark.

Stwertka, Albert.
The World of Atoms and Quarks.
New York: Twenty-First Century Books, 1995.
Traces the history of atomic theory in physics and includes a guide to elementary particles.

Web Sites

American Physical Society Education and Outreach
www.aps.org/educ/
Offers information on outreach activities including programs for women and minorities. The education programs section includes a downloadable guide that profiles current women physicists and provides tips for girls interested in pursuing a career in physics.

Beyond the 1930s Atom
www.tufts.edu/as/wright_center/lessons/pdf/docs/physics.html#atom
Provides seven activities relating to the Standard Model and offers a particle physics card game.

CERN Particle Acclerator Simulation
www.hep.ucl.ac.uk/masterclass/Acc_sim2/simulator.html
Displays an aerial photo of France and Switzerland overlaid with a graphic showing where CERN's accelerators reside; a simulation allows users to inject, speed up, and collide electrons and positrons.

The NIST Reference on Constants, Units, and Uncertainty
physics.nist.gov/cuu/Constants/index.html
Lists values of universal constants such as the Planck length and the speed of light in a vacuum; electromagnetic constants such as elementary charge; and atomic and nuclear constants such as masses for the electron, proton, neutron, and muon. Also includes a list of frequently used constants.

Hyperphysics
hyperphysics.phy-astr.gsu.edu/hbase/hph.html#hph
Presents a series of interactive concept maps with links to detailed explanations relating to core concepts found in electricity and magnetism, mechanics, relativity, quantum physics, and more.

The Particle Adventure
particleadventure.org/
Provides an interactive tour that explains what the world is made of and what holds it together, unsolved mysteries of the universe, how particle accelerators and detectors work, and more. Includes an online viewable and printable fundamental interactions poster.

QuarkNet for Educators
quarknet.fnal.gov/index_tchr.shtml
Contains classroom activities for analyzing particle physics data, building accelerator analogs, and constructing cosmic ray detectors.

Review of Particle Physics
pdg.lbl.gov/
Provides information about such topics as physical constants, the Standard Model, quantum dynamics, particle detectors, currently known particles, and more.

The Science of Matter, Space, and Time
www.fnal.gov/pub/inquiring/matter/index.html
Includes introductory information about the building blocks of nature and a timeline of the discoveries that led to the development of the Standard Model.

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www.pbs.org/nova/elegant/

String Theory

Books

Greene, Brian.
The Elegant Universe.
New York: Vintage Books, 2000.
Reviews major physics theories in depth, including Einstein's theories of special and general relativity and quantum mechanics. Explains in detail the specifics of string theory—from its multiple extra dimensions to its insights into black holes and cosmology—and the latest generation of the theory, known as M-theory. Includes many analogies to help elucidate these complex topics.

Gribbin, John R.
The Search for Superstrings, Symmetry, and the Theory of Everything.
Boston: Little, Brown and Co., 1998.
Offers an historical overview of subatomic particle physics, from the discovery of the electron in 1897 to some of the unification schemes being proposed today.

Peat, F. David.
Superstrings and the Search for the Theory of Everything.
Chicago: Contemporary Books, Inc., 1988.
Chronicles the search for unification of the four fundamental forces and details many aspects of strings, including why different theories call for strings to be open strands or closed loops, how strings interact, and how strings help explain black holes.

Articles

Arkini-Hamed, Nima, Savas Dimopoulos, and Georgi Dvali.
The Universe's Unseen Dimensions.
Scientific American, August 2000, pages 62–69.
Explains the concept of extra dimensions, where they may exist, and how they may be substantiated experimentally.

Johnson, George.
Almost in Awe, Physicists Ponder 'Ultimate' Theory.
The New York Times, September 22, 1998, page F1.
Traces the evolution of string theory and explains aspects of M-theory.

Weinberg, Steven.
A Unified Physics by 2050?
Scientific American, December 1999, pages 68–75.
Online at **www.sciam.com/issue.cfm?issueDate=Dec-99**
Summarizes the evolution of current theories of the nature of the universe and describes the possibility of a unified theory.

Weiss, P.
Hunting for Higher Dimensions.
Science News, February 19, 2000, pages 122–124.
Online at **www.sciencenews.org/20000219/bob9.asp**
Reviews various theories about extra dimensions and examines experiments designed to look for evidence of these.

Web Sites

The Official String Theory Web Site
www.superstringtheory.com/index.html
Includes basic and advanced descriptions of string theory principles and profiles physicists studying string theory.

String Theory: An Evaluation
www.math.columbia.edu/~woit/
Takes a critical look at various aspects of string theory.

String Theory and the Unification of Forces
theory.tifr.res.in/~mukhi/Physics/string.html
Provides a basic introduction to string theory and the Standard Model.

Superstrings
imagine.gsfc.nasa.gov/docs/science/mysteries_l2/superstring.html
Describes the basics of string theory and how it helps describe microscopic black holes; includes pop-up glossary.

Superstrings: Einstein's Dream at the New Millennium
www.nsf.gov/od/lpa/lecture/stringtheory.htm
Offers a streaming audio lecture by Sylvester James Gates Jr., director of the Center for String and Particle Theory at the University of Maryland. The 47-minute talk includes visuals and running text. (Requires RealPlayer plug-in.)

The Symphony of Everything
www.msnbc.com/news/201650.asp?cp1=1
Presents a simple, illustrated tutorial on string theory basics that includes information about string types, frequencies, and membranes.

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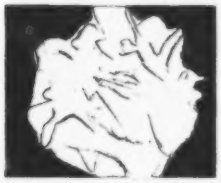
Glossary

big bang
The accepted theory that the universe began evolving some 13.7 billion years ago from an infinitely dense and hot substance that has been expanding since the first extremely small fraction of a second after its origin.

black hole
A region of space formed when an object collapses to the point where its gravitational field is so strong that it traps everything within its vicinity, including light.

Calabi-Yau shape
A configuration that could possibly contain the curled-up extra dimensions required by string theory. Tens of thousands of possible configurations exist; none have yet been verified to represent the additional dimensions predicted by string theory.



A Calabi-Yau shape is theorized to possibly hold the added dimensions required by string theory.

electromagnetism
One of four fundamental forces. Governs all forms of electromagnetic radiation, including radio waves, light, X-rays, and gamma rays. Also binds negatively charged electrons to positively charged nuclei. The residual electromagnetic force binds atoms and molecules. Acts over an infinite range.

elementary particle
Indivisible unit from which all matter is made and forces are communicated. Currently known elementary matter particles are grouped into categories of quarks and leptons and their antimatter counterparts. These particles interact through fundamental force carrier particles, which include the gluon, photon, and W and Z particles, and the theorized-but-undiscovered graviton.

extra dimensions
Additional spatial dimensions predicted by string theory beyond the three familiar extended dimensions; cannot be detected with current technologies. The initial version of string theory required six extra spatial dimensions; the more current version, M-theory, calls for seven extra spatial dimensions.

force carrier particle
Particle that mediates (transmits) one of the four fundamental forces. The gluon is the force carrier particle for the strong force; the photon is the force carrier particle for electromagnetism; the W and Z are the force carrier particles for the weak force; and the as-yet-unobserved graviton is the theoretical force carrier particle for gravity.

fundamental force
Any of the four natural forces: gravity, electromagnetism, the strong force, or the weak force. Transmitted by force carrier particles.

general theory of relativity
A theory developed by Albert Einstein that maintains that the force of gravity is the result of the warping of spacetime and that space and time communicate the gravitational force through this curvature.

graviton
A hypothetical particle thought to be the force carrier particle of the gravitational force.

gravity
The weakest of the four fundamental forces at the level of elementary particles; gravitation is the observed effect of the force of attraction between objects that contain either mass or energy; thought to be mediated by the theorized force carrier particle, the graviton. Acts over an infinite range.

hadrons
Particles built from quarks, such as protons and neutrons. Two types of hadrons exist: baryons (made from three quarks) and mesons (made from a quark and an antiquark). Governed by the strong force.

leptons
A family of elementary matter (or antimatter) particles that includes the electrically charged electron, muon, and tau and their antimatter counterparts. The family also includes the electrically neutral electron-neutrino, muon-neutrino, and tau-neutrino and their antimatter counterparts.

M-theory
A theory that unites five previous versions of string theory; predicts 11 spacetime dimensions and introduces membranes as one of the most fundamental elements in nature. M-theory is the latest incarnation of string theory ideas.

particle accelerator
A machine that speeds up particles before aiming them at a fixed target or colliding them together. Detectors capture the results of these particle interactions.

quantum field theory
A relativistic quantum theory that uses fields to describe the behavior of particles, especially during particle collisions. It describes how particles can be created and annihilated, as well as how they scatter in different directions and how they form bound states.

quantum mechanics
The physics theory that allows for the mathematical description of matter and energy consistent with their behavior as both particle-like and wave-like. It allows the calculations of probability of finding an object at a particular point in space and time, given its starting position and the forces acting upon it. The uncertainty principle of quantum mechanics (a manifestation of wave-like properties) implies that it is not possible to simultaneously know both the precise position and momentum of a particle.

quarks
A family of elementary matter (or antimatter) particles that includes the electrically charged up, charm, top, down, strange, and bottom quarks and their antimatter counterparts. Quarks make up protons and neutrons.

special theory of relativity
Einstein's theory that describes the motion of particles moving at any speed, even close to the speed of light. The theory proposes that the measured speed of light is a constant even if the source or observer of the light is moving. In contrast, measured distance, time, and mass all depend on the relative velocity of the source and observer.

Standard Model
A quantum-mechanical model that explains the three nongravitational forces—electromagnetism, the strong force, and the weak force—and their interactions with matter. Most of the particles predicted by the Standard Model have been indirectly observed or detected experimentally (the theoretical Higgs boson has not been confirmed). Gravity is not part of the Standard Model.

string
Tiny one-dimensional vibrating strands of energy that—according to string theory—make up all elementary particles. A string has length (about 10^{-33} centimeters) but no width.

strong force
The strongest of the four fundamental forces; binds quarks together and keeps protons and neutrons together in atomic nuclei. Mediated by gluons; acts over a short range.

superstring theory
A theory of the universe based on vibrating strings as the most fundamental units in nature; incorporates supersymmetry.

supersymmetry
The idea that all elementary matter particles have corresponding superpartner force carrier particles and that all force carrier particles have corresponding superpartner elementary matter particles. The theorized superpartners, thought to be more massive than their counterparts, have not yet been observed.

topology
The study of the properties of geometric figures or solids that demonstrate continuous transformations that are not changed by stretching or bending.

A coffee cup and a donut are topologically equivalent because both have a single hole.

weak force
One of the four fundamental forces; governs decay of elementary particles. Mediated by W and Z particles; operates over a short range.

wormhole
A theoretical structure in spacetime that forms a tube-like connection between two separate regions of the universe.

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